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FUNDAMENTAL MECHANISMS IN THE IONOSPHERE

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A LARGE number of experimental phenomena have shown the existence of an ionized region in the upper atmosphere extending roughly from 50 km to 400 km above the surface of the earth. This region, commonly known as the ionosphere, is characterized by a certain amount of stratification in ion density, and appears to be primarily, at least, of solar origin.

For the purpose of this paper it will suffice to review briefly some of the more fundamental experimental observations on the ionosphere. Qualitative observations of such radio transmission effects as fading, skip distance, the improvement of radio reception after sunset have been noticed by countless observers since the beginning of short wave radio transmission. These qualitative experiments have now been replaced by a quantitative technique whose details have been thoroughly mastered by groups working at various laboratories in the United States and abroad.

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I. Character of the Ionosphere

If a short pulse of electromagnetic waves of frequency f is sent out by an antenna, it is observed that an echo pulse will be received by an appropriate receiver t seconds after the reception of the directly transmitted ground wave. This phenomenon occurs provided f is *less* than a certain critical value known as the *critical frequency*. For values of f greater than the critical frequency, the signal will not be reflected but will be transmitted by the previously reflecting medium. This phenomenon arises out of a comparatively simple application of the ordinary equations of electrodynamics to an ionized

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medium, and the results may be condensed to a statement that an ionized medium possesses an index of refraction for an electromagnetic wave. The actual index of refraction varies with the frequency of the incident radiation and decreases with decreasing frequency. If μ, the index of refraction, can be made equal to zero, total reflection will occur for a wave with even normal incidence upon the medium, and the signal will be returned. Since μ is also a function of the charge density, an experimental measurement of the critical frequency, or the frequency at which the signal just ceases to be returned, affords at once a measurement of charge density in the ionized region. Obviously, a distance to the reflecting layer may also be calculated if the time be measured between the reception of the ground wave and the echo wave and if the disturbance be assumed to travel with the speed of light. Such a calculated height is known as the virtual height and may not be the actual height of the layer owing to the decrease in velocity of the wave as it travels through ionized regions whose charge density is not sufficient to reduce the index of refraction to zero.

The problem is not quite as simple as outlined above owing to the fact that the process described takes place in the magnetic field of the earth. This can be shown to give rise to a double refraction and polarization of the returned waves with both an ordinary and an extraordinary ray as in optics. The charge density, N, of a region whose critical frequencies are f_{ord} and f_{ex} are given by the equations

$$N=(\pi m/e^2)f_{\text{ord}}{}^2$$

and

$$N=(\pi m/e^2)(f_{\text{ex}}{}^2-f_{\text{ex}}f_H), \quad \text{where} \quad f_H=eH/2\pi mc,$$

where e is the electronic charge, m the mass of the ionized particle, c the velocity of light and H the value of the earth's magnetic field. In the case of the ordinary wave, if plane polarized, the electric vector is parallel to and independent of the magnetic field of the earth, while in the case of the extraordinary wave, the electric vector is normal to the magnetic field. In the latter case the frequency is partially dependent upon the value of the earth's field through the precessional term $f_H=eH/2\pi mc$. Furthermore, it may be noted that a single measurement of a critical frequency does not specify exactly the number of charged particles present, but can give only the ratio N/m. If singly charged particles of different mass exist, then the expressions for the frequencies must be summed over all types of masses existing. It is thus apparent that the actual number of ions may be 10^3 times the number of electrons, yet the charge density of the latter will be largely responsible for the reflection of the wave. The difference between the critical frequency of the ordinary and extraordinary wave does depend, however, upon the mass of the charged particle. Thus this quantity, when measurable, should be of the greatest interest. It may also be noted that N is a measure of either the number of positively or negatively charged particles since these numbers are equal in an atmosphere which is electrically neutral.

A large number of critical frequency observations have been made in the last ten years and certain general facts established. Three layers or regions seem fairly definite—a D region at about 50 km with comparatively weak ionization which disappears at night; the E region or Kennelly-Heaviside layer at about 100 km which is moderately ionized, strongest at noon and in summer and decreases in strength at night; and the F region with strongest ionization at 200–400 km. The E region disappears in high latitudes in winter which indicates that even though in this case it can be illuminated by sunlight from below, the effective ionizing agent has been completely absorbed by its first passage through the atmosphere. The F region during the day appears to be split into two layers, the F_1 and the F_2 regions, which merge at night into a single layer. The heights of the E and F_1 layers are roughly constant, but the height of the F_2 layer appears to be roughly inversely proportional to the ion density. This also does not follow as regular a behavior as the lower layers, but is higher and less ionized in summer than in winter and does not necessarily show a maximum at noon.

Other ionized regions have been reported and abnormal changes in the ionization of the regularly occurring layers, but these are situations which must be left for special discussions.

Insofar as the source of the ionization is concerned, it seems practically conclusive that all ordinary ionospheric phenomena may be ex-

plained by the hypothesis that they arise from absorption in the upper atmosphere of extremely short wave-length ultraviolet radiation from the sun. This has been definitely established for the E and F_1 layers whose behavior during eclipses has been studied and whose source of ionization shown to be solar and to travel with the velocity of light. A similar explanation will probably hold for the F_2 layer although the experimental evidence is not as conclusive. The disappearance of the D layer at night also points to its solar origin.

The physicist is thus confronted with a series of observational facts which imply a gas subject to photoionization and which subsequently undergoes changes in ion content when the source of ionization is removed or diminished. Processes of photoionization, electron and positive ion recombination, negative ion formation, and the recombination of positive and negative ions must therefore play a fundamental role. Fortunately all these processes have been the subject of extensive theoretical and experimental investigation in the laboratory, and it is the purpose of this discussion to consider the present status of laboratory knowledge in this respect.

II. Character of the Upper Atmosphere

Before laboratory data may properly be discussed, it is necessary to consider briefly the general character of the upper atmosphere. It has often been suggested that in a gaseous medium subject to gravitational attraction, and free from vertical mixing, the component gases should distribute themselves according to the well-known hypsometric equation

$$n = n_0 e^{-mgx/kT},$$

in which n is the number of molecules at height x, m the mass of the molecule, k the Boltzmann constant, and T the absolute temperature. If this were the case, the character of the upper atmosphere should change with height beyond the level where vertical transport and mixing ceases. The character of the change is such that the proportion of lighter gases in the upper atmosphere should rapidly increase, ultimately becoming largely hydrogen. Observations of several sorts, however, argue against an atmospheric composition (at least up to levels of 150 or 200 km) which is markedly different from that at the surface. The samples of air from 29 km studied in the recent stratosphere investigation of the National Geographic Society[1] showed a composition almost identical with the normal surface composition. The existence of winds in the lower stratosphere is well known by direct pilot balloon observations to levels far above the tropopause. Meteor trains have been observed to indicate wind velocities of considerable magnitude at levels of 100 km. Furthermore much spectroscopic evidence has now been obtained by direct observation of night sky light and auroral light. Such spectroscopic evidence is uniformly in agreement in attributing the observed lines and bands to known transitions of oxygen and nitrogen in both the atomic and molecular state. No evidence of hydrogen has ever been obtained. It therefore seems reasonable to assume that the composition of the atmosphere up to levels of 130 km (the level assumed in the well-known calculations of Maris[2]) is the same as at sea level and in isothermal gravitational equilibrium beyond that level. On this basis Maris has calculated values of the molecular density for various levels in the atmosphere. Such a table, taken from a recent paper by E. O. Hulbert,[8] is reproduced in Table I. To this table have been added values of the electron charge density N, the pressure p, and the time between collisions. Since it now seems quite possible that oxygen at least in the upper atmosphere exists in the atomic rather than the molecular form, a second set of values of the molecular density has been computed on the basis that the oxygen is atomic beyond the 100 km level. The computation of molecular densities of this sort obviously depends greatly upon the extent and character of the mixing

TABLE I.

Z (km)	N	n (MARIS)	n (ATOMIC O)	PRESSURE (mm Hg)	TIME BETWEEN COLLISIONS
60		9.9×10^{15}	9.9×10^{15}	.28	3×10^{-7} sec.
100	2×10^{5}	1.6×10^{14}	2.2×10^{14}	4.5×10^{-3}	1.5×10^{-5}
160		7.7×10^{11}	2.2×10^{12}	2×10^{-5}	3.2×10^{-3}
200	3×10^{5}	2.5×10^{10}	2.1×10^{11}	7×10^{-7}	0.1
300		7.7×10^{6}	9.9×10^{8}	2×10^{-10}	10^{2}
	10^{6}				
400		4.1×10^{5}	5.1×10^{6}	10^{-11}	10^{4}

assumed, upon the temperature, and upon the character of the molecular species. The majority of the evidence seems to point to a temperature of the outer atmosphere which is somewhat warmer than ordinary stratosphere temperatures, and is probably of the order of 300 or 400°K with probably lower temperatures at night. Evidence for the substitution of atomic masses rather than molecular, at least for oxygen, is of several sorts. First may be noted the well-known formation of ozone in the atmosphere which causes the cutoff of the solar spectrum at about 2900A and whose amount is equivalent in thickness to about 3 mm of O_3 at NTP. The formation of ozone must essentially involve a photodissociation process and the length of time spent in the atomic state will increase as the time between collisions subsequent to dissociation increases. Moreover, if it is to be assumed that the ionization of the upper atmosphere is of photonic origin, a known dissociation process which occurs at lower energies can hardly be ruled out. It has also been suggested by Chapman[3] that the source of energy for the various bands and lines representing the light of the night sky may be adequately ascribed to absorption of energy emitted by recombining oxygen atoms. Finally, the values of the ionic density obtained by critical frequency measurements predict almost *total* ionization of the atmosphere in the F levels, even assuming the negatively charged particles to be electrons. Thus it seems probable that one must discuss processes which can occur for both atoms and molecules and that the molecular densities of Maris given in Table I are somewhat lower than actually obtain. Such a table affords, nevertheless a useful guide for thinking in considering the physical properties of the region under consideration.

III. Photoionization

Theoretically, radiation of frequency ν greater than that given by the relation $eV = h\nu$ where V is the ionization potential of the atom or molecule should be capable of removal of an electron by direct ionization. With this in mind, the physical characteristics of the atmospheric gases to be ionized may be considered. The first ionization potential of N_2 occurs at 15.55 volts and the second (producing N_2 in the A' excited state) occurs at 18.68 volts. These energies correspond to wave-lengths of 794A and 661A, respectively. Which of these actually is the lower limit for ionization is a matter of interest in estimating the available solar energy for such a purpose. The absorption of nitrogen in the far ultraviolet has been studied by Hopfield[4] who found continuous absorption beginning at 660A and not at 794A. It thus appears, and this is in agreement with results on other diatomic molecules, that the lowest ionization potential is not strongly affected by radiation of the proper frequency, and that higher ionization potentials have much greater probabilities. The case of nitrogen is further complicated by the existence of a metastable level at 6.2 volts. This level is associated with the well-known Vegard-Kaplan bands in the light of the night sky, and the cumulative ionization of N_2 should be possible in two stages if a sufficient number of such excited molecules are present. Under these conditions the absorption of light of a frequency corresponding to 1030A should be sufficient for ionization to the A' level.

Turning to the oxygen molecule, we find that the ionization potentials to be 12.5 and 16.1 volts. Experiments of Price and Collins[5] show that as in the case of nitrogen, no continuous absorption sets in at 990A, but several systems of bands passing to *a continuum* at energies corresponding to 765A (16.14 volts) and 740A (16.7 volts) are found. The absorption coefficient given by Price and Collins is such that strong absorption occurs in 0.01 mm pressure and path of 1.5 meters. While direct ionization of the O_2 molecule occurs with these energies, nevertheless another process occurs in O_2 which appears to be relatively infrequent in N_2—namely dissociation of the molecule. At low pressures, this is known to occur for wave-lengths less than 2040A. The ionization potential for the oxygen atom is 13.55 volts corresponding to 913A. If the process of dissociation has left one of the atoms of oxygen in the ^1D state, then light of wave-length 1065A is sufficient for ionization. The data for available energy in the solar spectrum have been calculated by use of a black body distribution of energy for a body at 6800°K. Obviously such a calculation is extremely sensitive to choice of temperature, it may be noted at once, however, that these values are rather far removed from those necessary to

maintain the observed ionization. Accordingly it has been frequently suggested that the sun's radiation in the far ultraviolet differs markedly from that of a black body and that the output of such radiation is much greater than that given by the above table.

Unfortunately little or no data exist for absorption coefficients in the far ultraviolet. Pending laboratory experiments of these interesting quantities, they must be inferred from ionosphere data themselves.

Occasionally it has been reported that air can be ionized by radiation which can pass through a fluorite window. As the limit of transparency of ordinary fluorite is about 1300A, this might be a matter of importance in the ionosphere. The question, however, has been investigated by Loeb and Varney[6] and found to be answered definitely in the negative. Hence the wave-length values given above must be those upon which attention is to be focused.

It is not to be thought that all wave-lengths beyond the actual ionization potential are equally effective in causing ionization. The probability of photoionization has not been investigated experimentally for oxygen and nitrogen, nor do theoretical calculations exist for these particular molecules. In several excellent papers, however, Mohler[7] has investigated the photoionization of various metallic vapors and found that the maximum probability of ionization occurs shortly beyond the series limit and falls off fairly rapidly for higher frequencies. This, of course, will not affect any energetic arguments presented by Table II since the less absorbable radiation (i.e., the higher frequencies) will merely penetrate farther through the atmosphere and will ultimately be absorbed and produce ionization. It may be noted that the magnitude of experimental atomic absorption coefficients at the point where ionization occurs are of magnitude of 10^{-17} to 10^{-19}. These obviously are values which may be considered in connection with the molecular densities given in Table I and show that the observed heights of the ionization are in approximate accord with this hypothesis of its origin. This has been discussed in detail by Hulbert[8] and Chapman.[9]

TABLE II.

ENERGY LESS THAN	IONIZING	QUANTA/CM²/SEC.
1030A	Metastable N_2	1.4×10^{11}
990	O_2	7.05×10^{10}
913	O	1.4×10^{10}
794	N_2	5.4×10^{8}
765	O_2	2.2×10^{7}
660	N_2	4×10^{6}

From the above it is seen that the number of available photons for ionization per cm²/sec. may be obtained from certain assumptions concerning the solar radiation, and it is further seen that the absorption of these photons will take place in general above 100 km. It will be the aim of succeeding sections of this paper to discuss the disappearance of the positive ions and electrons formed by photoionization, and to estimate the efficiencies of the various processes.

IV. Recombination of Positive Ions and Electrons

The recombination of positive ions and electrons is a process which is the exact reverse of photoionization. In the former a quantum of light interacts with a molecule ejecting an electron and leaving a positive ion. In the latter case, a positive ion and an electron recombine with the emission of radiation. The radiation emitted will not necessarily be that required to ionize the atom—in fact it will generally be degraded to lower frequencies as the atom or molecule returns to its ground state by successive electron jumps. Thus the radiation, having once ionized is not available for successive ionizations. The rate of recombination for densities of ions and electrons n_+ and n_-, is given by the familiar equation

$$dn/dt = -vq(v)n_+n_-$$

where $q(v)$ is the effective cross section for electrons of velocity v or πd^2 where d is the distance between the ion and the original path of the electron. This path must be such that enough energy is lost by radiation to permit capture into a closed orbit. Ordinarily, of course, owing to the inverse square law of force between the particles, the path is a hyperbola and capture will not take place. Owing to the reciprocity of the photoionization mechanism and the capture mechanism, the familiar Einstein relation exists between the absorption coefficient and the capture cross section. This states that

$$vq(v) = \alpha(v) = kB(\nu\nu_i)\nu^3/(\nu-\nu_i)^{\frac{1}{2}},$$

in which ν and v are related by the equation

$$h\nu = h\nu_i + \tfrac{1}{2}mv^2.$$

Since $B(\nu\nu_i)$ is finite at the series limit, the coefficient of recombination of electrons and positive ions must be a function of the velocity of the electrons such that it varies for low energies as $1/v$. In the ionosphere, which is assumed to be electrically neutral, the electrons must be in thermal equilibrium with their surroundings, and the recombination coefficient will vary as $1/T^{\frac{1}{2}}$ where T is the absolute temperature. Although the electrons presumably have something of a Maxwellian distribution of velocities the actual recombination coefficient remains proportional to $1/T^{\frac{1}{2}}$.

Direct experimental measurement of the coefficient of recombination of electrons and positive ions has never been accomplished in the laboratory. Most attempts of this nature which have endeavored to measure the coefficient of recombination in the usual way have been vitiated, either by impure gases in which negative ion formation occurred, or by stray fields due to contact potentials which were sufficient to remove the electrons before recombination could take place. The only measurements upon which reliance may be placed are those which arise out of recombination spectra. As mentioned above, the recombination of positive ions and electrons gives rise to the emission of frequencies corresponding to the various lines of a series plus a continuum beyond the series limit which owes its origin to the initial kinetic energy of the electron. Measurements of this recombination spectra and its decay with time enable estimates to be made of the capture cross section and hence the coefficient of recombination. There will, of course, be different values depending upon into which level capture is considered, and it is desirable, where possible to speak of the sum of such capture cross sections for all different levels. Kenty[10] has found a value of q of 5×10^{-18} cm^2 corresponding to $\alpha=2\times10^{-10}$ for 0.4 volt electrons in argon. For electrons of thermal energies, this value should then be about 10 times greater or 5×10^{-17} cm^2. This may be assumed to be the order of magnitude of the value for other gases.

In passing it should be mentioned that a means of directly measuring the recombination coefficient of electrons and positive ions should be a very worthwhile experiment if it could be carried out with modern technique.

V. Formation of Negative Ions

The formation of negative ions has been studied in many gases and the essential features of the phenomenon are fairly well understood from both theory and experiment.

Negative ions are formed when a molecule possesses a stable state into which an extra electron can be bound. This electron is held with a definite energy and it is quite permissible to speak of the ionization potential of the negative ion, or what is more commonly known as its electron affinity. Both molecular and atomic oxygen possess positive values of electron affinity. No direct measurement of the ionization potential of the negative O_2 molecule has been carried out, but some experiments of Loeb[11] coupled with a theoretical study by Bloch and Bradbury[12] show the order of magnitude of the value of the electron affinity to be 0.20 volts. The electron affinity of the oxygen atom is known from experiments of Lozier[13] to be 2.2 volts. Nitrogen molecules in the normal state do not appear to possess an electron affinity and negative ions have not been observed in pure nitrogen under ordinary conditions. However, a qualitative study by Bradbury[14] has shown that the presence or absence of an electron affinity is a function of the electronic configuration of the molecule—the essential feature being that a molecule must possess some uncombined spin or orbital electronic momentum before capture in a stable state becomes possible. This at once precludes capture by all molecules whose state is $^1\Sigma$. The normal state of oxygen is, however, a $^3\Sigma$ and negative ions are formed. In the case of nitrogen, the normal state is $^1\Sigma$ and the absence of negative ions is verified by experiment. As mentioned above, however, there exists a metastable state of nitrogen which is a $^3\Sigma$ configuration. If the life of this state is sufficiently long, capture by these excited states may be possible. An attempt to observe this phenomenon in the laboratory is to be carried out by Loeb.

The major problem in the formation of negative ions is the disposal of the energy corre-

sponding to the binding energy of the extra electron plus the kinetic energy carried in by the electron. In many cases of negative ion formation, this process is facilitated by the dissociation of the molecule whose fragments then carry away the energy released by ion formation on one of them. Such a process is not energetically possible in oxygen, at least, with electrons of thermal energies. There remain as processes liberation of energy by radiation and some sort of a three-body process in which a neutral partner in the collision may be available to carry away the excess energy.

The formation of negative ions with the emission of radiation has been considered by Jen[15] for the simple case of the hydrogen atom which is theoretically known to possess an electron affinity of 0.7 volt. He finds that the capture process for 1-volt electrons has a cross section of 1.6×10^{-22} cm². Furthermore, the absorption coefficient remains finite and substantially constant between 1 volt and zero and therefore the cross section for slower electrons may be obtained from the Einstein-Milne relation and will rise as $1/v^2$. It may be noted that it is this type of process which must describe any negative ion formation with oxygen atoms as no other means (excluding three-body processes) are available. The process, however, depends upon the cube of the emitted frequency and therefore will be approximately $(2.2/0.7)^3$ times greater or about 5×10^{-21} cm² for 1-volt electrons and O atoms, although the exact calculation for this element has not been carried out. Considering O_2 molecules we may compute a cross section of $(0.20/0.70)^3\times1.6\times10^{-22}=4\times10^{-24}$ cm² for the radiative capture process.

The formation of negative ions with oxygen molecules has been measured experimentally by Bradbury[16] for pressures greater than 3 mm. For electron energies of 0.3 volt, the cross section is about 1×10^{-19} cm² corresponding to a chance of attachment at a kinetic theory collision of 1.8×10^{-4}. The cross section is rapidly increasing for lower electron energies. Since the value of this cross section is 10 to 100 times greater than that for a radiative capture process, a different mechanism for this type of ion formation has been suggested by Bloch and Bradbury.[12] They suggest that excitation of the first vibrational state of the oxygen molecule occurs as the result of the combined energy of electron affinity and kinetic energy of the incoming electron. The vibrational energy so acquired is then lost at a subsequent collision with a neutral molecule. This is essentially therefore a three-body process and should therefore be pressure dependent. However, the radius of the molecule for transfer of the excitation energy is sufficiently large so that the pressure dependence does not show up at pressures above 5 mm. There is some evidence to indicate that at lower pressures the formation of negative ions in O_2 occurs with less rapidity. It therefore seems reasonable to assume that this type of negative ion formation in oxygen becomes pressure dependent at about 1 mm pressure and decreases linearly with pressure thereafter. Thus at a pressure of 0.01 mm (approximately that of the E layer) the value of the effective cross section for 0.3 volt electrons will be 10^{-21} cm². This may be compared at this energy with the approximate value for radiative capture 1.33×10^{-23} cm².

The theory of the excitation process, however, at once shows that the cross section cannot increase indefinitely with decreasing kinetic energy of the electrons inasmuch as eventually a point will be reached where the kinetic energy of the electron plus the binding energy is insufficient to excite the first vibrational state. At this point the probability of capture rapidly falls off, any capture at all being due in fact to those electrons in the higher energy region of the normal distribution curve. Depending somewhat on the value assumed for the electron affinity, this drop occurs at about 0.10 volt mean electron energy.

The various processes described in this section may be summarized for purposes of discussion in the following table which is calculated for approximately the conditions of the E and F layers of the ionosphere assuming an electron temperature of 300°K. It is thus seen from Table III that

TABLE III.

PROCESS	q (CROSS SECTION)	VELOCITY VARIATION	PRESSURE VARIATION
$O+\epsilon\rightarrow O^-+h\nu$	1.3×10^{-19} cm²	$1/v^2$	None
$O_2+\epsilon\rightarrow O_2+h\nu$	1.7×10^{-22} cm²	$1/v^2$	None
$O_2+\epsilon\rightarrow O_2^-$	8×10^{-22} cm² (.01 mm) 8×10^{-28} cm² (10^{-3} mm)	v^2 for low energies	$1/p$
$\epsilon+O_2^+\rightarrow O_2$	5×10^{-17} cm²	$1/v^2$	None

only the process of formation of negative oxygen atoms has a cross section which is comparable with that of recombination with positive ions. However, the equations which will describe the loss of particles per unit time will depend not only on these cross sections, but on the number of particles available for the process. That is, one has

$$\underset{\text{Recombination}}{dn/dt=-v(q(v))n_+n_-} \qquad \underset{\text{Attachment}}{dn/dt=-vq'(v)nn_-}$$

and hence the ratio of the rates of loss will be

$$\text{Loss recombining/Loss attaching}=\frac{n_+\ q_{\text{recomb}}}{n_0\ q_{\text{capture}}}.$$

Hence although $q'(v)$ may be small the greater number of neutral molecules relative to positive ions in the lower layers may make this process predominate. Since there is a ratio of about 1.6×10^4 between the total number of particles and the number of charged particles calculated on a *molecular* mass for the E layer, the possibility of this layer being at least partially ionic is not ruled out. For the remaining layers, negative ion formation must be excluded as an important process relative to recombination of positive ions and electrons.

VI. Recombination of Positive and Negative Ions

Many studies have been made of the values of the coefficient of recombination of ions. Such experiments coupled with the theoretical studies of J. J. Thomson and Loeb and Marshall[17] have now led us to a satisfactory understanding of the mechanism of the attachment process. Briefly, unless an ion can undergo a collision with a neutral molecule within a sphere of a certain radius surrounding the ion of opposite sign, the ion will execute a hyperbolic path and recombination will not take place. The radius of this sphere is defined by the consideration that at that distance the thermal energy of the ion is equal to the potential energy of one ion in the field of the other. Ions outside this sphere will in general diffuse apart—and those ions which drift within will execute hyperbolic orbits unless by collision they lose part of their kinetic energy gained from the field. Recent experiments of Gardner[18] in highly purified oxygen have verified the Thomson equation providing a mass of twice the mass of molecular oxygen be assumed and a mean free path of 1/5 the kinetic theory value. Both of these assumptions are in accord with previous knowledge of the behavior of ions under ordinary pressures. The shortening of the mean free path is due to the effect of the charge of the ion on neutral molecules possessing a dipole moment and the mass 64 represents an attached neutral molecule.

Gardner has studied the coefficient of recombination of ions in oxygen as a function of pressure and temperature. The complete equation gives

$$\alpha=1.90\times10^{-5}(273/T)^{\frac{1}{2}}(1/M)^{\frac{1}{2}}\epsilon,$$

where $\epsilon=2w-w^2$

and $w=1-(2/x^2)[1-e^{-x}(1+x)]$

with $x=0.81(273/T)(p/760)(\lambda_A/\lambda)$.

For low pressures, i.e. small x, such as exist in the ionosphere, $\epsilon=4/3x$. From this it is seen that the recombination coefficient for the Thomson process will vary directly as the pressure, inversely as the square root of the mass of the ions, and inversely as the 5/2 power of the temperature. For temperatures between -70°C and 200°C and for pressures between 10 cm and atmospheric these predictions have been verified by Gardner.

For the E region of the ionosphere with an assumed pressure of 0.01 mm and a temperature of 300°, Gardner's results and Thomson's theory predict a value for the recombination coefficient of 3.8×10^{-10}. A lower limit must be set to the applicability of this theory as has been pointed out by Loeb[19] since there must be added the probability that two ions will recombine upon direct collision. The collision frequency of N_1 particles of type 1 with N_2 particles of type 2 is known from the kinetic theory to be $2\pi N_1N_2\sigma_{12}^2(c_1^2+c_2^2)^{\frac{1}{2}}$ which for our purposes becomes $\pi N_1N_2\sigma^2c$ upon the assumption of equal masses for the particles. This at once gives another expression for the coefficient of recombination and must be added to the Thomson expression. For very low pressures, and even in the E layer unless the effective collision-capture radius is very small, this type of recombination will predominate over the Thomson type and is pressure independent. Assuming the kinetic

theory value for the collision-capture radius, we get $\alpha = 1.85 \times 10^{-10}$. This value is of the same order as that predicted by the Thomson theory and the effective radius may well be larger than that assumed.

The recombination of positive and negative atoms should be susceptible to this same calculation, but no values are known for the effective collision radii. Furthermore, unless a third body can cooperate in the process, such a recombination will not result in reforming the molecule.

VII. Conclusion

The several processes which have been discussed in the light of laboratory experiment are now in a position to be applied to ionospheric theory. When coupled with proper diffusion equations, the application of the experimental relations to the equilibrium state during the day, and the variation at night when the ionizing source is removed should further elucidate the character of the light emitted in the far ultraviolet part of the solar spectrum and enable definite hypotheses to be formulated regarding the character of the charged particles in the upper atmosphere as well as temperature changes in the upper atmosphere.

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To ponder on the future life of man and on the ability of science to mold and reform the future is to lift oneself to a plane of high buoyance. In the words of the Earl of Balfour, in an address he made as president of the British Association, "The satisfaction it gives is almost esthetic in its intensity and quality. We feel the same sort of pleasurable shock as when, from the crest of some melancholy pass, we first see far below us the sudden glory of plain, river and mountain."

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TERRESTRIAL MAGNETIC VARIATIONS AND THE IONOSPHERE*

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THE conception of a conducting layer of the upper atmosphere was first hypothesized by the British physicist, Balfour Stewart,[1] in 1882 in order to explain the diurnal variations of terrestrial magnetism. These he believed due to the electrical currents flowing at great heights in electrically conducting regions of the atmosphere, induced by the electromotive forces resulting from tidal movements of the earth's atmosphere across the lines of force of the vertical component of the earth's magnetic field. This suggestion of Stewart was further investigated by Schuster[2] and by Chapman.[3] The former, carrying out a suggestion of Gauss, examined the diurnal variations of terrestrial magnetism by spherical harmonic analysis, and demonstrated that the variations arose primarily from causes outside of the surface of the earth, a minor portion being due to such currents as would be induced by the primary external field. Schuster is responsible for the first mathematical treatment of the theory. Velocities of the tidal movements of the atmosphere are approximately derivable from a velocity-potential ψ which is most simply related to barometric pressure p by the equation $d\psi/dt = v^2\,\delta p/p$, v being the velocity of sound in air.

Solution of the differential equations relating the various factors involved leads to a current-system similar to that depicted in Fig. 1. In this figure two foci may be perceived, one in the northern hemisphere and one in the southern hemisphere. This current-system in Fig. 1 is that which would be necessary to produce the diurnal variations of terrestrial magnetism observed in the western hemisphere. Special attention is directed to the major features of the current-flow which are important to subsequent considerations.

This entire theory antedated the accomplishment of transatlantic radio communication and many of the principal features of what we now know as the ionosphere had been inferred from the facts of terrestrial magnetism. More definite ideas concerning the electrical state of the earth's outer atmosphere developed with the advancement of knowledge concerning the properties of gases which permit them to conduct an electrical current.

The major ionizing agent was believed to be ultraviolet light from the sun, and in accordance with this belief laws for the variation of electrical conductivity as a function of the sun's zenith-angle were formulated.

Accomplishment of transoceanic radio communication led Kennelly and Heaviside[4] independently to hypothesize a region of the upper atmosphere capable of reflecting radio waves. Its existence was definitely demonstrated[5] by the radio experiments of Breit and Tuve and of Taylor and Hulburt in this country, and of Appleton in England. By means of these experiments it is possible to measure the equivalent electron-density at various heights in the reflecting regions.

Radio waves of a given frequency are reflected

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when the number of electrons per cubic centimeter has a certain value. The experimental technique[6] involves a transmission of pulses of radio waves approximately ten times per second. Reflections of these pulses are oscillographically recorded. The time interval between the transmission and the reception of the pulses is a measure of the virtual heights of the layer from which it is reflected, while the frequency of the wave which penetrates the layer gives a measure of the ionic (or electronic) density.

A sample record is reproduced in Fig. 2. The lines in the figure consist of innumerable points of light, photographically recorded. The frequency of the transmitted waves is varied with time so that as the photographic paper slowly moves across the light-slit a record of reflections at all frequencies is obtained. In Fig. 2 the ordinates correspond to heights and the abscissae to frequencies. The interpretation of this photographic record is presented at the right of the figure. The straight line at the bottom of the figure is the base-line representing the exact instant of transmission. The first line above is produced by the wave reflected from the lower or E layer, the second by that reflected from the F_1 layer, and the uppermost by that reflected from the F_2 layer. The strong upward slope of the reflected pattern indicates proximity of a critical frequency of penetration, the group-velocity becoming very small as the wave penetrates a layer resulting in great increases in virtual height. Doubling of lines, particularly noticeable near the critical frequency, is due to magneto-ionic double refraction.

Recent research on the upper atmosphere by means of radio wave reflection has resulted not only in a substantiation of the basic conceptions regarding that region inferred from the terrestrial-magnetic variations, but also has added detailed information regarding finer features of the upper atmospheric structure. Radio data have revealed the existence of three layers of ionization—the E layer at a height of approximately 100 km, where the frequency of molecular collision is comparatively high, and the F_1 and F_2 regions above about 200 km where molecular collisions are much less frequent. The equivalent electron-densities for these upper layers are appreciably greater than that for the lower layer.

Theoretical considerations derived from the study of an ionized gas reveal that the medium is not an isotropic conductor in the presence of a magnetic field if the gyromagnetic frequency of the ions (or electrons) is comparable with or greater than their collisional frequency.[7] The electrical conductivities perpendicular to the magnetic field and parallel to the magnetic field are related to each other by the formula $\nu^2/(\nu^2+\omega^2)$, ν being the collisional frequency and ω the gyromagnetic frequency. For very low collisional frequency the conductivity perpendicular to the magnetic field becomes negligible. Thus, since the electric currents proposed by the theory of Stewart in general flow perpendicular to the earth's magnetic field, doubt has been cast upon the adequacy of the electrical conductivity of the atmosphere for the explanation of the mechanism. This difficulty led to the proposal of a diamagnetic theory by Gunn[7] and of a drift-current theory by Chapman[8] as alternates to the theory of Stewart. Both of these theories depend upon the behavior of ions in the region of low collisional frequency, whereas, from the considerations previously mentioned, it is observed that if the mechanism proposed by Stewart is responsible for the diurnal variations it must

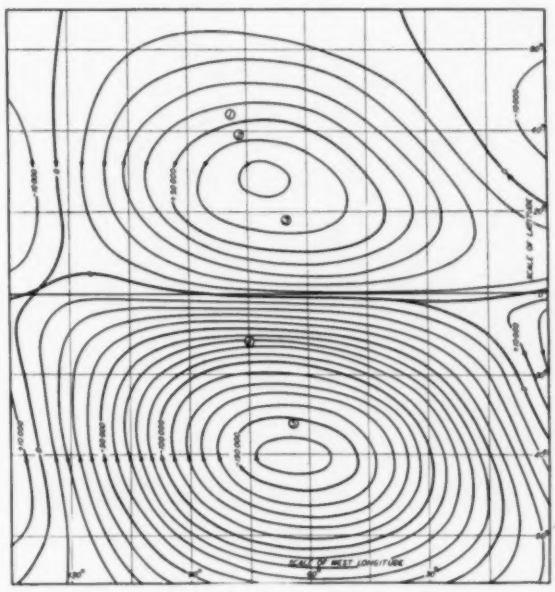

FIG. 1. Isometrics of external current function, western hemisphere, amperes at 11^h 75° west meridian time, international quiet days, equinox 1923, deduced from magnetic diurnal-variations at Agincourt (1), Cheltenham (2), Vieques (3), Huancayo (4), and Pilar (5).

apply in the lower portion of the ionosphere where collisional frequency is adequate.

Observational evidence demonstrating which region of the ionosphere is responsible for the diurnal variations thus supplies sound basis for discriminating between the various theories of the magnetic variations. Exactly such evidence has been obtained during the past year and a half by the observation of radio fadeouts on high frequencies accompanied by special disturbances of the earth's magnetic field. Attention was first called to these phenomena by J. H. Dellinger[9] of the National Bureau of Standards, who suggested that they were caused by some special solar phenomena. Examination of solar records by the Mt. Wilson Observatory, at his request, revealed the correctness of his suggestion. The fadeouts were found to have occurred at times when bright hydrogen eruptions were observed in the solar chromosphere.

One of the most spectacular and noteworthy of these occurrences is reproduced in all its aspects by Fig. 3. These phenomena occurred on April 8, 1936, during routine observations with the spectrohelioscope at the Huancayo Magnetic Observatory of the Carnegie Institution of Washington.[10] The observer on duty was scanning the sun's disk in accordance with a prearranged program, when he noticed a sudden brightening of the *H*-alpha line in the region of a large sun-spot. This brightening began at $16^h\ 45^m$ GMT. By $16^h\ 47^m$ the flare of light had reached its maximum intensity. At the same time the radio observer engaged in measuring critical frequencies and virtual heights of the reflecting regions at the observatory ceased to receive echoes from the upper atmosphere. Suspecting difficulties with his equipment, he made a careful examination, found it satisfactory and resumed his observing program. At $17^h\ 50^m$ echoes were again received and all layers of the ionosphere appeared to be in a comparatively normal state.

The next day when the photographic records of the magnetic variations regularly recorded at the observatory were developed, a large and unusual change in the magnetic force was noticed coincident in time with the radio fadeout and beginning just one minute after onset of brightening in the sun-spot. Records of the natural electrical currents flowing in the earth's crust regularly made at the observatory showed an increased departure from the normal trend.

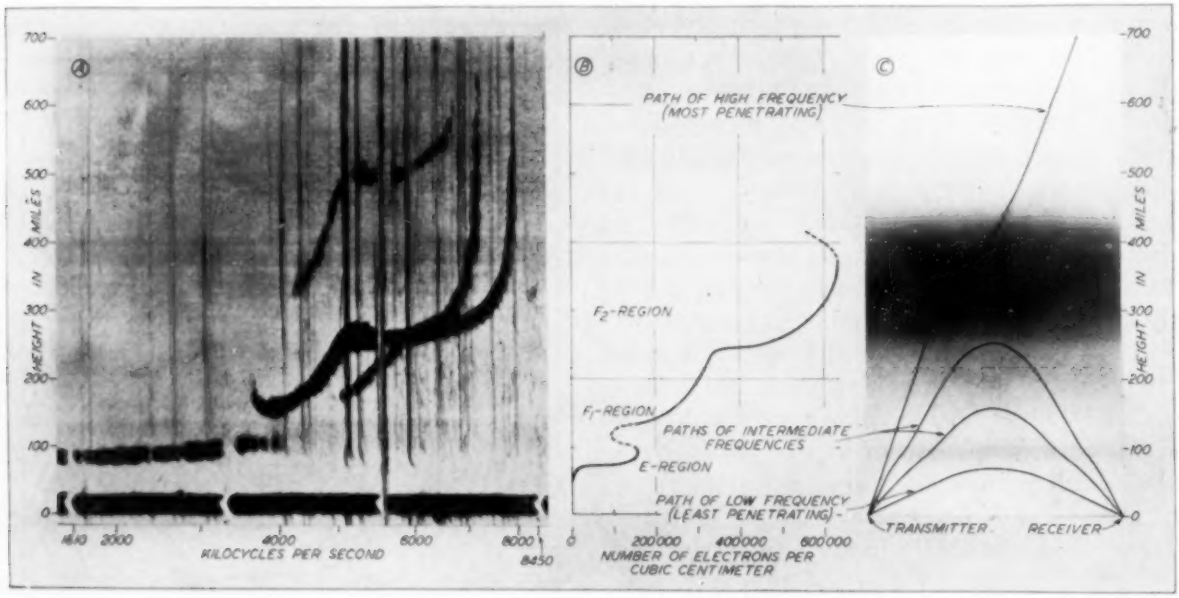

FIG. 2. Exploration of the ionosphere. (A) Typical record of heights of ion-densities obtained with automatic variable-frequency equipment at Kensington, Maryland, 3 P.M., May 15, 1936; (B) distribution of ions deduced from (A); (C) density of ionization deduced from (B) showing paths of waves of various frequencies. [Diagram (C) shows transmitter and receiver separated for simplification, although in actual work the radio transmitter and receiver are at same station and the wave paths are vertical.]

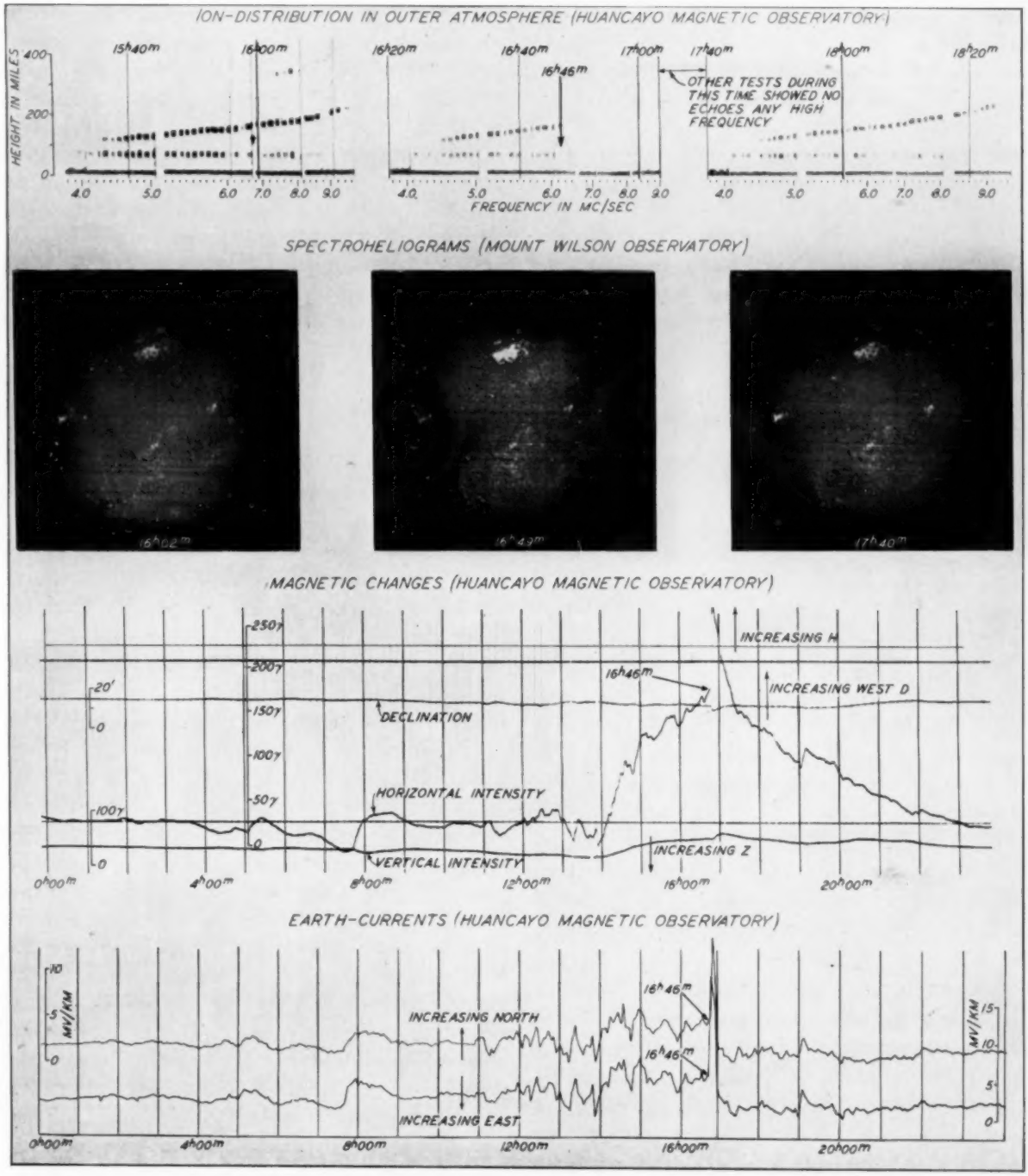

FIG. 3. Magnetic, radio, and earth-current disturbances associated with brilliant solar eruption, April 8, 1936 (Greenwich mean time throughout).

Fortunately, photographic records of the sun's disk taken in *H*-alpha light were available from the Mt. Wilson Observatory during this period, supplying the permanent record of the chromospheric eruption. The actual photographic records are reproduced in Fig. 3.

It is of immediate interest to know in what regions of the ionosphere these processes occur. The radio data show definitely that the fadeout occurs because of strong absorption of the radio

wave at levels below 100 km. Fig. 4 shows the ionospheric record on May 28, 1936, during a fadeout. The ionospheric equipment was set to operate on a continuous frequency—4.8 mc per

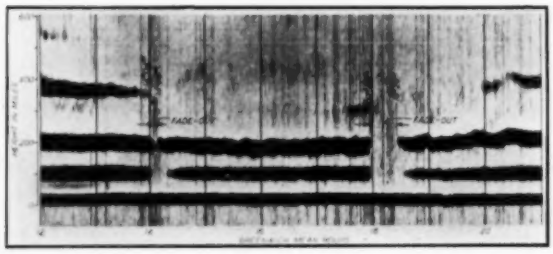

FIG. 4. Example of radio fadeouts, Huancayo Magnetic Observatory, May 28, 1936.

sec. At this frequency, a regular reflection is returned from the F_1 layer, and a weaker boundary-reflection is obtained from the E layer. These reflected waves together with the ground-waves are represented by the three horizontal lines in Fig. 4. A fadeout occurred at $14^h\ 04^m$ GMT. Both the border and regular reflections were suddenly cut off, and the first reflection to reappear was the stronger F_1 reflection, the weaker border-reflection from the E layer not being received until several minutes later. Another fadeout occurred on the same day at $17^h\ 58^m$ as shown on the record. Since both the E and F_1 layers were in a substantially unchanged condition at the end of the fadeout, and since reflections were received from the F_1 layer while the E layer reflections were still out, it appears that the effect was due to absorption of the radio wave at the base of or below the E layer.

Such absorption is attributable to the formation or enhancement of a layer of ionization where the frequency of molecular collision is high. It is likely that this takes place in the same region in which broadcast frequencies are ordinarily absorbed during daylight hours and from which very long waves are reflected. This view is further supported by evidence published by R. Bureau,[11] who observed an increase in intensity of low frequency atmospherics during fadeouts of high frequency waves.

A striking confirmation of these inferences is supplied by Fig. 5, taken from a paper by Berkner and Wells.[12] This figure consists of 30 successive 15-minute records of the virtual heights and critical frequencies of the ionospheric layers made by a newly developed automatic multifrequency equipment of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, operating at the Kensington (Maryland) Experimental Station during a fadeout which occurred on July 31, 1936. Through each 15-minute interval the frequency of the transmitted wave is continuously varied from 16.0 to 0.516 mc per sec.—time progresses from right to left in the figure—and the reflected waves are oscillographically recorded as previously described.

The first record shows distinct reflections from the E, F_1 and F_2 layers with three multiple reflections appearing above the F_2 reflection. In the second record the second and third multiples do not appear, which marks the first perceptible effect of the fadeout. All multiple reflections, the lower or E layer reflection, and part of the F_1 reflection fail to appear on the eighth record. No reflections from any layers appear on the ninth to the eleventh records—the interval of total fadeout. The F_2 layer reflection appears faintly in the twelfth record after which all reflections gradually reappear in the inverse order of their disappearance.

Clearly, the lower frequencies, which are ordinarily reflected from the E, F_1 and F_2 layers, are most strongly absorbed by the increased ionization; also, since the multiple reflections disappear first, the weaker signals are more strongly absorbed. The F_2 layer, for the time during which it is "visible" through the absorbing layer, shows no change in virtual height or critical frequency. These observations seem compatible with only one possibility—the creation or great enhancement of an absorbing layer at the base of or below the E region. They also demonstrate that the radiation producing this absorbing layer passes through the upper layers without causing any measurable change in their ionization.

Careful study of the magnetic records made during the fadeout of April 8 and subsequent fadeouts on August 24 and November 6, 1936, at the Huancayo Observatory, and at numerous other observatories widely distributed over the surface of the earth, has furnished a compre-

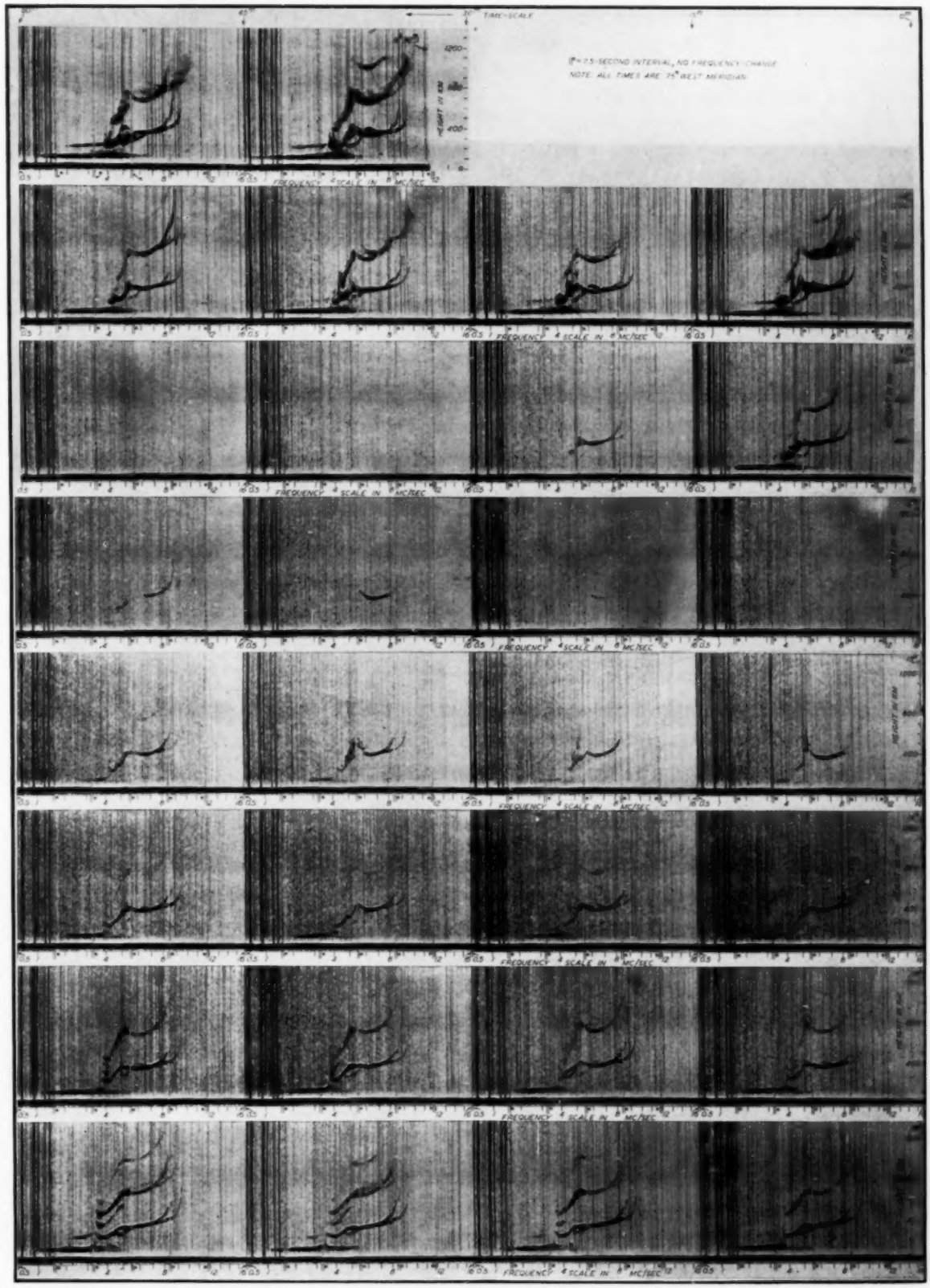

FIG. 5. Ionospheric virtual heights multifrequency records, Kensington, Maryland, July 31, 1937, for 0.516 to 16.0 mc/sec. over 15-minute periods from $9^h\ 32.5^m$ to $17^h\ 00^m$.

hensive picture of the nature of the magnetic changes taking place.[13] The overhead currents, assumed to flow in the ionosphere, which would produce the observed magnetic effects are represented in Fig. 6, compared with the corresponding currents necessary to produce the normal variations obtained at the time of fadeout on November 6. The light arrows represent the direction and magnitude of the normal diurnal-variation current, while the heavy arrows show the additional current necessary to produce the special magnetic disturbances occurring during the fadeout. The special characteristics of these effects are that both systems of arrows are nearly parallel and that they correspond in their distribution to the current-system of the normal diurnal variations presented in Fig. 1. No effect was observed at San Juan, which was near the center of the system of circulation at time of occurrence, nor were effects observed at stations far from the center of circulation. It may be concluded from this that the magnetic effects are confined to the daylight hemisphere, although one fadeout, which has not yet been studied in detail, was accompanied by magnetic effects extending slightly beyond the twilight zone.

Current arrows for the fadeout of August 25, 1936, are shown in Fig. 7. In this case the subsolar point was much further to the northwest, permitting strong effects to occur at Sitka and Meanook which exhibited no effects on November 6, while Coimbra and San Miguel, which previously exhibited an effect, are found to lie outside the system of circulation.

The most interesting magnetic effects were observed in connection with the fadeout on April 8 shown in Fig. 8. The general system of circulation closely resembles that portrayed in Figs. 6 and 7. The center of circulation should be expected to lie close to San Juan—the current at that station is found to be small—but a reversal in the direction of the current takes place between Mt. Wilson and Teoloyucan.

Emphasis is placed on the anomalous direction

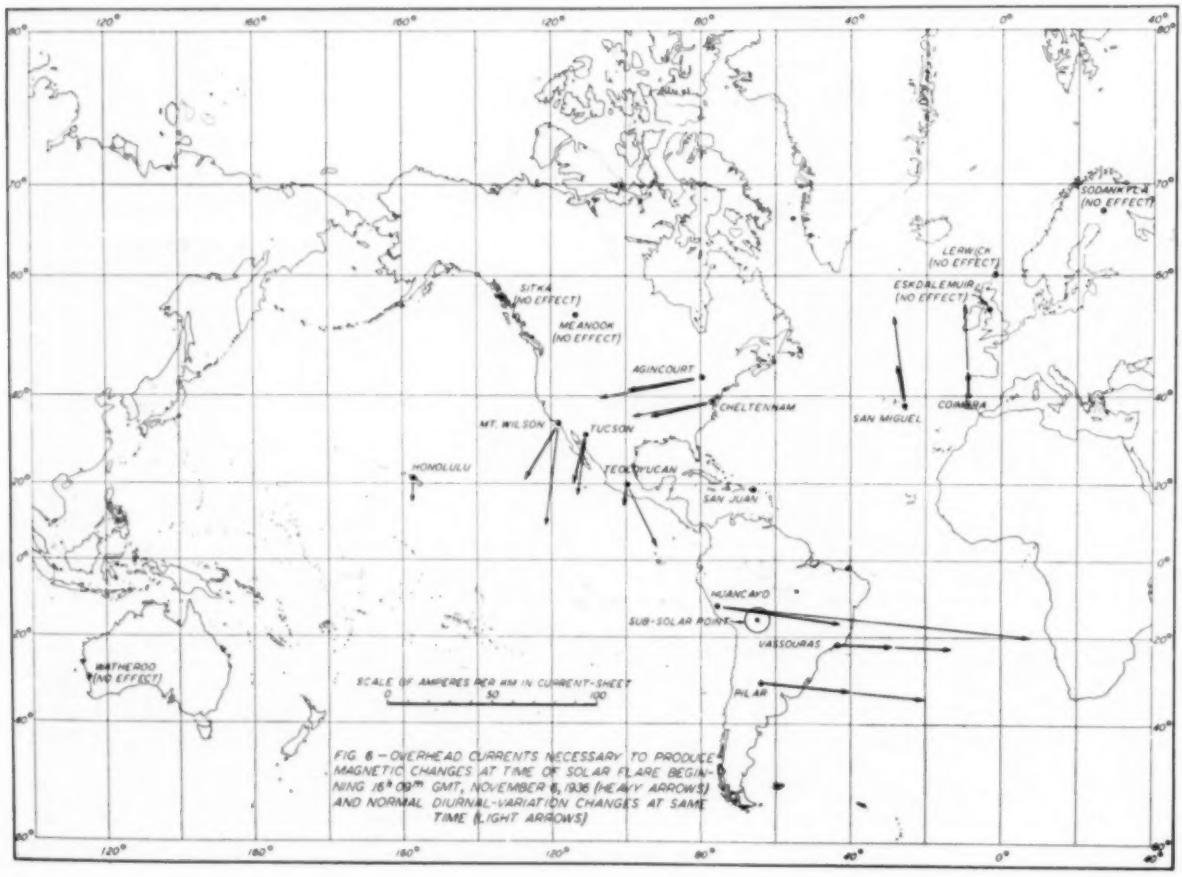

FIG. 6—OVERHEAD CURRENTS NECESSARY TO PRODUCE MAGNETIC CHANGES AT TIME OF SOLAR FLARE BEGINNING 16h 09m GMT, NOVEMBER 6, 1936 (HEAVY ARROWS) AND NORMAL DIURNAL-VARIATION CHANGES AT SAME TIME (LIGHT ARROWS)

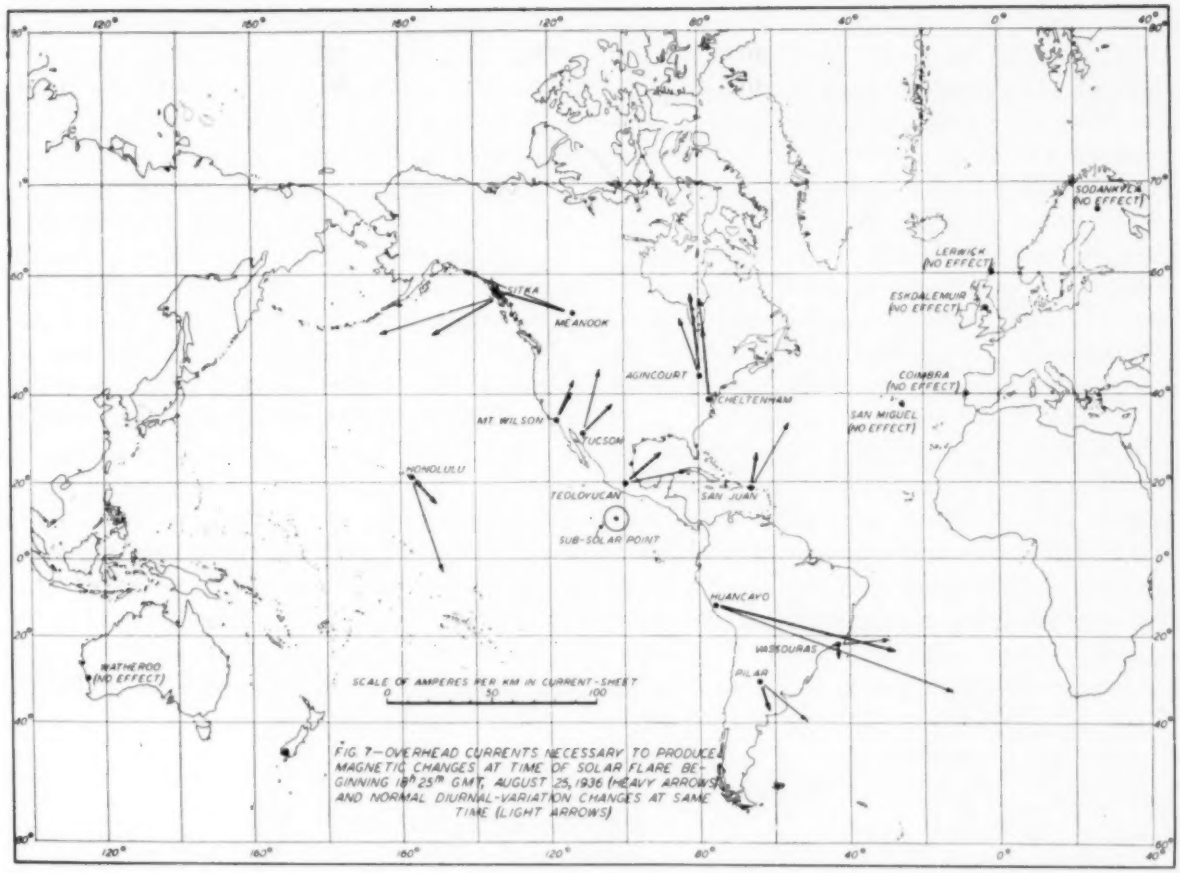

FIG. 7—OVERHEAD CURRENTS NECESSARY TO PRODUCE MAGNETIC CHANGES AT TIME OF SOLAR FLARE BEGINNING 18h 25m GMT, AUGUST 25, 1936 (HEAVY ARROWS) AND NORMAL DIURNAL-VARIATION CHANGES AT SAME TIME (LIGHT ARROWS)

of the current at Teoloyucan. Both the arrow representing the current producing the special disturbance and the arrow representing the normal diurnal variation current exhibit the anomalous direction. No explanation of this anomaly is offered—the important fact is that both the diurnal variation and fadeout effects are in the same direction in spite of the anomaly. Thus it is clear that the current system causing the special disturbance at time of fadeout is an increase in the normal diurnal variation current, and not an independent system which merely simulates it since it reproduces even the anomalies of the diurnal variation current. This is strong evidence that the extra current producing the special disturbance flows in the same region of the upper atmosphere where the normal diurnal variation current flows. It is presumed to arise through improved conductivity caused by the increased ionization which also causes the absorption of radio waves.[14] Therefore, the normal diurnal variations of terrestrial magnetism must also be caused by effects in the lower portion of the atmosphere to which the theory of Balfour Stewart would assign them, and not in the vaster upper regions which would be the seat of the drift-current and diamagnetic effects since radio data indicate unambiguously that this increase of ionization occurs at the base of or below the *E* region while higher regions are not affected. Observation of these special disturbances constitutes the strongest support which the theory of Stewart has had.

Explanations offered for radio and magnetic effects are entirely compatible. Since both begin coincidently with the observation of brightening in the chromospheric eruption and since both are manifested only on the side of the earth toward the sun, the active agent proceeding from the sun must be light-radiation—probably the extreme ultraviolet spectrum of hydrogen since the eruptions are manifested by a brightening of the *H*-alpha line. In the ordinary solar spectrum this line is dark, but in the light proceeding from an

intense eruption it exceeds the adjacent continuous spectrum of the sun's disk in brightness. The gases emitting light in these eruptions appear to be thrown to great heights above the chromosphere where ultraviolet light may escape from the sun without strong absorption. The heights to which the gases are thrown are more favorable for the emission of the higher energy lines and the continuum of the hydrogen spectrum. It is possible that other abundant elements of the solar chromosphere may be responsible for much of the ultraviolet light, though no evidence on this point is yet available.

The increase in the ionizing radiation may be inferred from the magnitude of the magnetic changes. During the three cases studied the electric currents flowing in the ionosphere appear to be doubled, consequently the ionizing radiation responsible for the conductivity where the magnetic diurnal variations have their origin must increase by a factor of at least four. During the fadeout of April 8 this increase occurred within four minutes suggesting that the increase in the ionizing radiation was even greater.

As the decay of the currents was quite rapid, implying rapid recombination of the ions, the number of ions ordinarily present in this region must be large. A large number of ions is also required by the Stewart theory to account for the normal conductivity. Therefore, it does not seem possible to reconcile the ion-density of the lower region of the ionosphere with the intensity of solar ultraviolet light if the sun radiates as a black body. Since the effects which have been described appear due to bright-line emission—no increase in black-body radiation can be detected in these chromospheric eruptions—it is reasonable to suppose that ordinary solar radiation may consist of bright lines in the extreme ultraviolet which contribute far more energy than black-body radiation in that region. In fact when consideration is given the normal ionization supported by the sun this view is compelling.

Consideration has been given only to a special

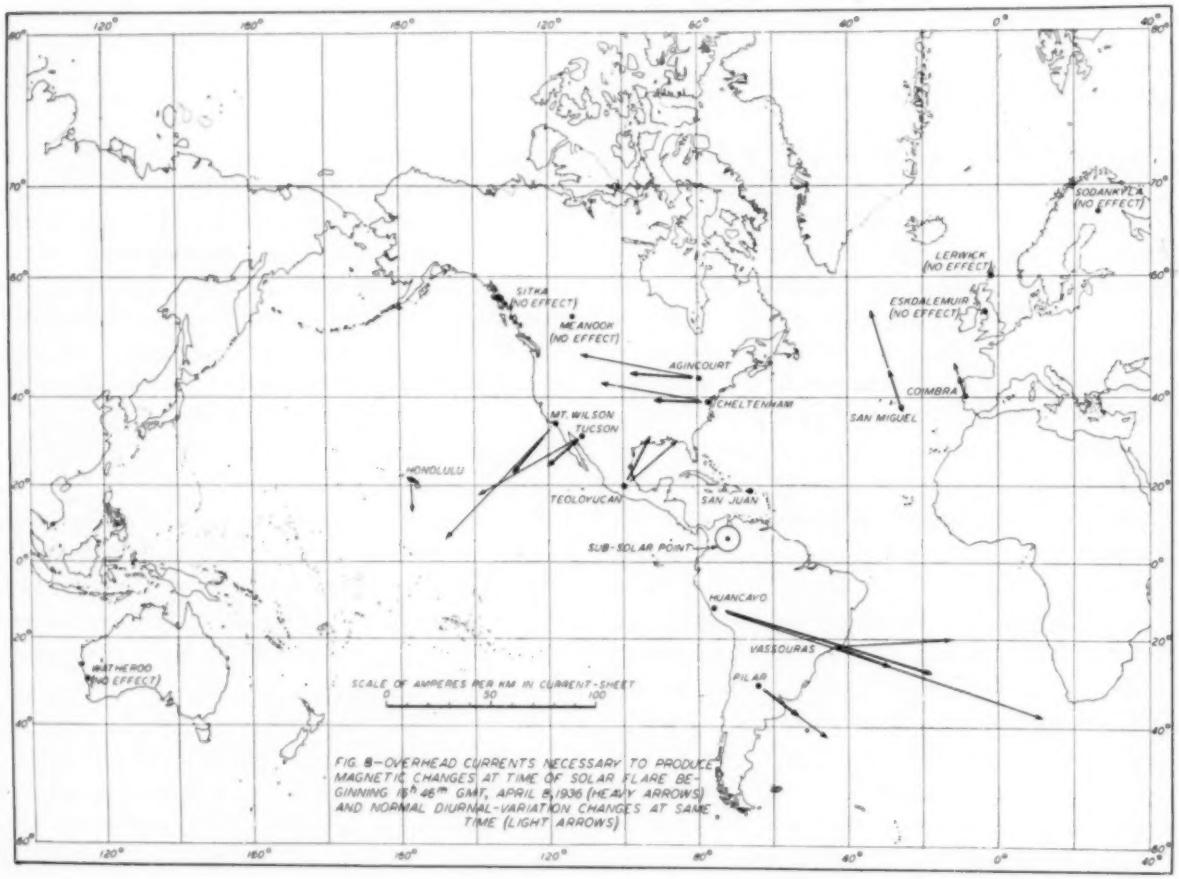

FIG. 8—OVERHEAD CURRENTS NECESSARY TO PRODUCE MAGNETIC CHANGES AT TIME OF SOLAR FLARE BEGINNING 16h 46m GMT, APRIL 8, 1936 (HEAVY ARROWS) AND NORMAL DIURNAL-VARIATION CHANGES AT SAME TIME (LIGHT ARROWS)

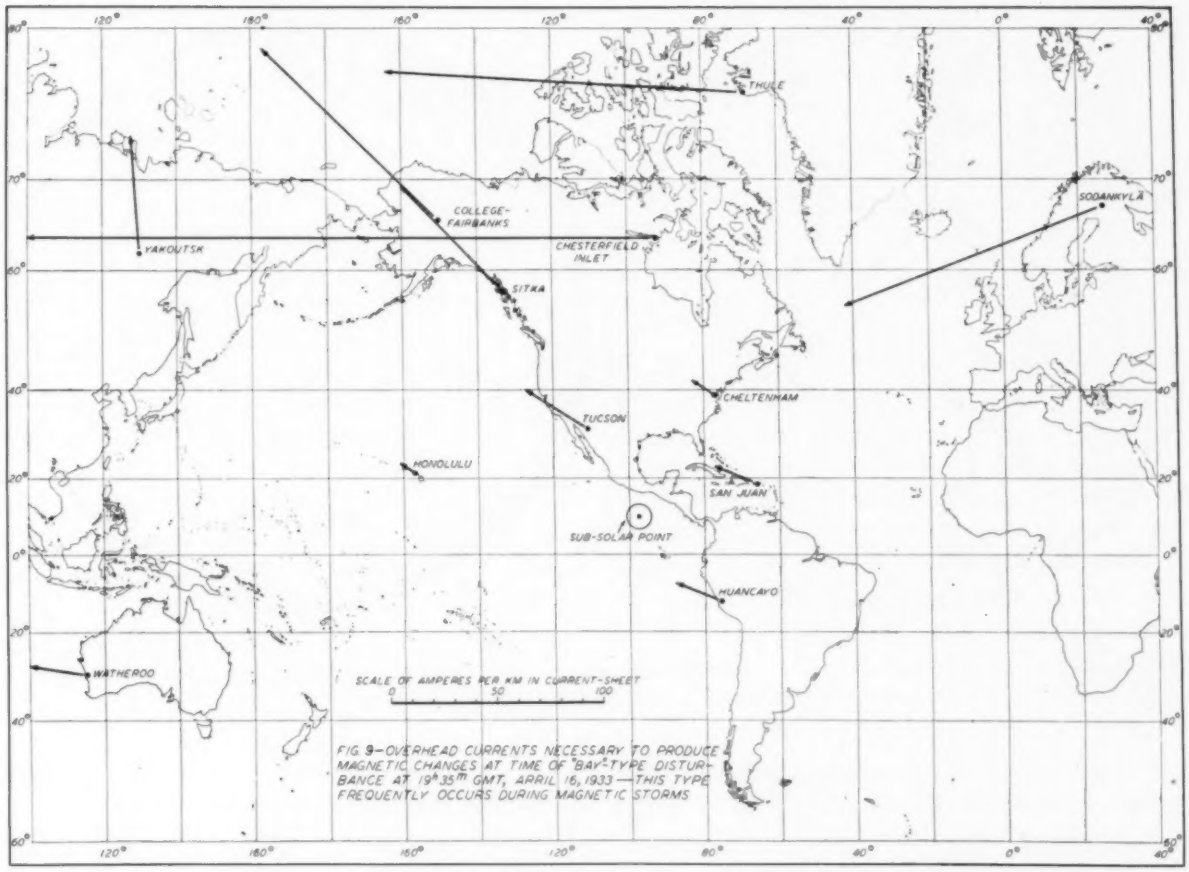

FIG. 9—OVERHEAD CURRENTS NECESSARY TO PRODUCE MAGNETIC CHANGES AT TIME OF "BAY"-TYPE DISTURBANCE AT $19^h 35^m$ GMT, APRIL 16, 1933—THIS TYPE FREQUENTLY OCCURS DURING MAGNETIC STORMS

type of magnetic phenomena associated with radio effects. These are phenomena closely associated with the normal diurnal variations of terrestrial magnetism. Other magnetic phenomena occur which are associated with radio effects in an entirely different way. These are magnetic storms.

There is no reason for supposing any connection between chromospheric eruptions and magnetic storms although both are associated with sun-spot activity. It may be that sun-spots in which eruptions are occurring are most likely to produce magnetic storms but no definite relationship has been established. The ionospheric currents necessary to produce the "bay"-type disturbances of the earth's field, common during a magnetic storm, are illustrated by an example in Fig. 9. While the currents flowing during a fadeout are greatest in equatorial regions the currents of the bay-disturbance are greatest in high latitudes.[15] Also, the bay-disturbance is not confined to the side of the earth toward the sun.

One characteristic feature of magnetic storms is a world-wide decrease in the horizontal component of the earth's magnetic field which lasts for a day or several days. The ionospheric currents necessary to produce this effect are shown in Fig. 10.[16] Another characteristic feature is the sudden onset of a magnetic storm, usually manifested over the entire earth by a distinct type of magnetic change. All of these magnetic effects and the currents necessary to produce them differ markedly from those associated with radio fadeouts and chromospheric eruptions. While the disturbances associated with chromospheric eruptions are clearly due to ultraviolet light, the most promising theory of magnetic storms attributes them to the action of corpuscles, charged and uncharged, emitted by the sun. Deflection of the charged corpuscles by the earth's magnetic field would account for the strong manifestations of storms on the dark side of the earth and their intensification in a high latitude belt called the auroral zone. Likewise in

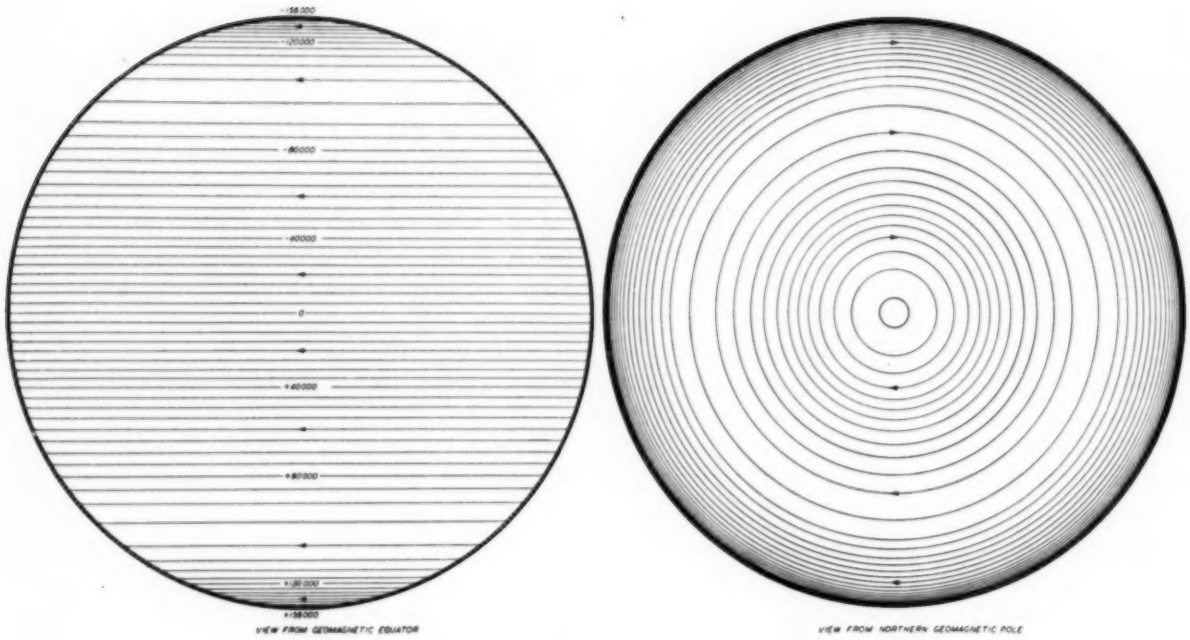

FIG. 10. Isometrics of equivalent external current function in amperes in spherical shell 100 km above earth's surface for magnetic storms, disturbed day minus quiet day differences, 1927.

their effect on radio transmission magnetic storms are markedly different from the fadeouts accompanying chromospheric eruptions.

During the most intense magnetic storms radio transmission on high frequencies is very difficult if the path of the wave passes close to the auroral zone. Transmission over paths lying in tropical regions is not appreciably affected. This condition is likely to persist through most of the disturbed period. A graphical representation of this fact is presented in Fig. 11 in which "percentage commerciality"—percentage of the time-circuits were satisfactory for commercial use—for North Atlantic radio circuits is plotted against intensity of magnetic disturbance as measured by the American character figure for individual days.[17] The area represented by a small black square signifies a single day. On the three days during the interval when the magnetic character figure exceeded 1.95—2.00 denotes maximum intensity of disturbance—the North Atlantic circuits were satisfactory for commercial use less than 12½ percent of the time, while the majority of the days when conditions were satisfactory had a character figure 0.15 or less. Fortunately for radio communication intense magnetic storms are unusual.

Knowledge of magnetic storms and the times when they are likely to occur is important to radio traffic engineers. Forecasts of magnetic conditions have been used successfully in arranging for international broadcasts. Advantage has been taken of the fact that transmission over

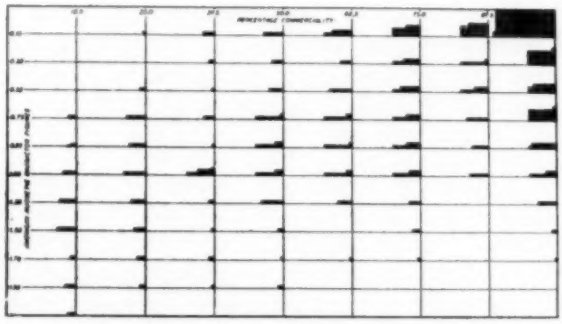

FIG. 11. Relation magnetic storminess and quality trans-atlantic radio reception on individual days, May 28, 1928 to December 31, 1930.

low latitude paths is not severely affected by magnetic storms. During intense magnetic storms high frequency radio traffic between North America and Europe has been maintained by routing the messages through South America, thereby avoiding proximity of the paths to the auroral zone.

Length series of observations of the earth's magnetic field dating back for a century have furnished much information on the occurrence of magnetic storms. It has long been known that magnetic storms follow the 11-year sun-spot-cycle—magnetic storms being most frequent and most intense at times of sun-spot maxima. A plot of magnetic activity and relative sun-spot numbers is shown in Fig. 12.[18] Magnetic storms exhibit another outstanding feature—quiet days and disturbed days, magnetically, tend to recur at 27-day intervals. This quasi-periodic effect may persist for several months at a time, after which one series of disturbances dies out and another appears. The effect may be explained by assuming that active areas on the sun emit corpuscular streams of limited diameter. These areas rotate with the sun and at 27-day intervals arrive at a meridian so located that the corpuscles may impinge on the earth. Apart from their practical importance in permitting prediction of magnetic storms the 11-year and 27-day periods serve to establish solar activity as the cause of magnetic storms.

The mechanism whereby magnetic storms are produced is not satisfactorily explained. The assumption of a corpuscular origin is supported by observations of auroras which occur with magnetic storms and which seem to be due to incoming corpuscles. The means whereby corpuscles get into the earth's field and produce the observed magnetic effects constitute a difficult problem. The world-wide change in magnetic force is such as would be produced by an electric current flowing in the upper atmosphere parallel to circles of latitude with density roughly proportional to the sine of the latitude, as shown in Fig. 11, or to a large ring current circulating about the earth from east to west like the rings of Saturn. Chapman and Ferraro[19] have attempted to explain the formation of this ring-current by assuming a stream of charged particles of both signs entering the magnetic field of the earth, the stream itself being electrically neutral. The corpuscles of opposite sign would be curved by the earth's field and so encircle the earth. The stability of such a ring-current is open to question.

An increase of ion-density in the ionosphere might be expected at times of magnetic storms. However, the radio data show that on days of magnetic storms the maximum ion-density of the F region frequently decreases in low and middle latitudes.[20] On the other hand ionospheric observations conducted near the auroral zone indicate an increase in ion-density in the lower portions of the ionosphere during magnetic disturbance and auroral displays which is believed to absorb the frequencies ordinarily reflected from the F region.[21] The observations do not preclude the possibility that the total ionization may be greater although more diffuse.

Paradoxically, although magnetic storms appear to decrease the maximum ion-density of the F_2 region the average maximum ion-density of the region is greatest during years of high sun-spot numbers, that is, when magnetic storms are most numerous.[22] This variation is illustrated in Fig. 13 showing the critical frequency at noon determined by the National Bureau of Standards at Washington, D. C., and by the Department of Terrestrial Magnetism at Watheroo, Western Australia. From 1934 to 1937 the average annual value of critical frequency is approximately doubled. Since critical frequency is proportional to the square of ion-density and since ion-

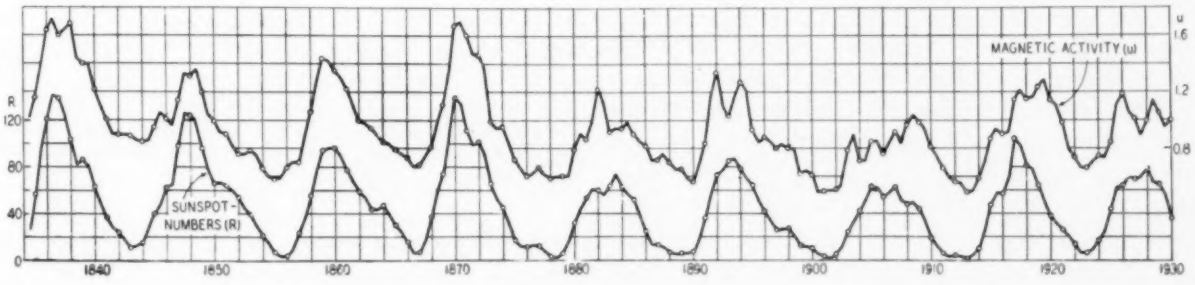

FIG. 12. Annual means of magnetic activity and sun-spot numbers, 1835–1930.

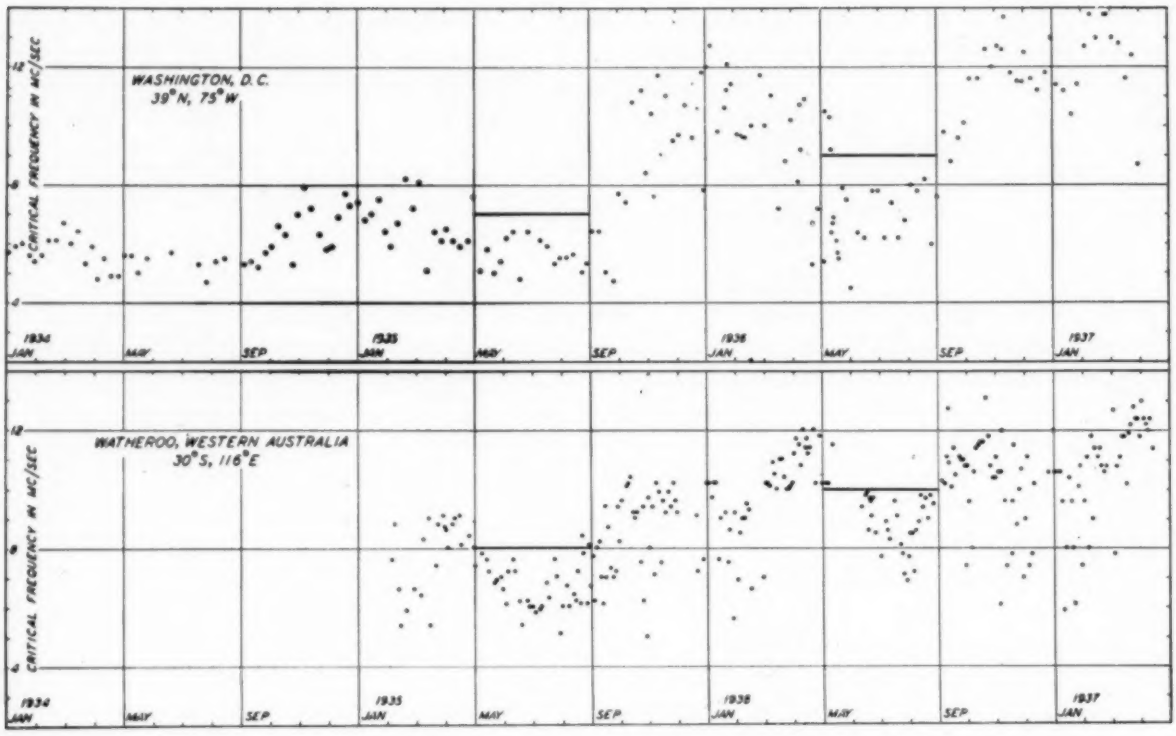

FIG. 13. Comparison noon critical frequency F_2 region.

density, for equilibrium, is proportional to the square of the rate of ion-production, the ionizing agent must have increased by a factor of four.

A pronounced diurnal variation in ion-density has been noted for all layers of the ionosphere. The E and F_1 layers attain their maxima shortly after noon, the F_2 layer in the late afternoon or evening. At night and, in the high latitudes during large solar declination, the F_1 and F_2 layers are merged into one. These facts indicate solar origin for all the layers and lead to expectation of corresponding seasonal variations. Paradoxically again, as shown in Fig. 13, the maximum ion-density of the F_2 layer is greatest around the December solstice in both the northern and southern hemispheres.[22] These changes are too great to be attributed to the difference in solar distance from one solstice to another.

Thus, while conceptions of the lower ionosphere and the normal magnetic diurnal variations are becoming more definite, study of magnetic storms and the upper ionosphere reveals many facts, inconsistent with preconceived ideas and apparently inconsistent with each other. The ionization of the E and F_1 layers is produced by solar ultraviolet light—upon that there can be no doubt. Radio observations at times of solar eclipse, as shown in Fig. 14, strongly support this

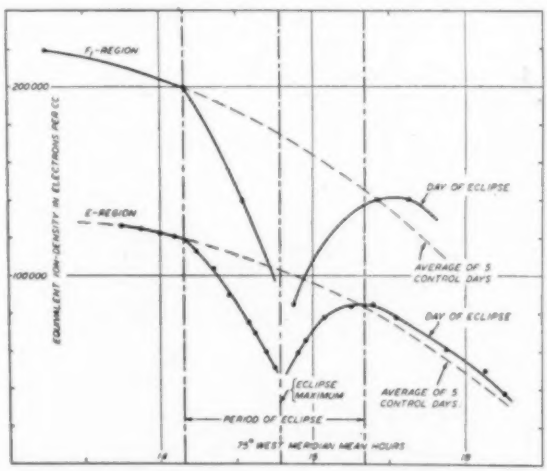

FIG. 14. Solar eclipse effect in E and F_1 regions on August 31, 1932, Kensington, Maryland (after Kirby, Berkner, Gilliland, and Norton).

view.[23] No simple ultraviolet theory can account for the phenomena observed in the F_2 layer. The fact that the F_2 layer is most affected during a

magnetic storm suggests that corpuscles may play a part in its ionization. However, a decrease in ion-density seems to occur while an increase would be expected. Large fluctuations in ion-density are inconsistent with the concept of fairly constant solar radiation. Since visible bright hydrogen eruptions in the solar chromosphere produce marked increases in ionization below the *E* layer it is reasonable to suppose that other fluctuations may occur in the extreme ultraviolet portion of the solar spectrum which would give rise to the observed effects. However, the investigation of these effects, in addition to improving our understanding of terrestrial phenomena, permits inferences regarding that portion of the solar spectrum which man may never be able to observe directly.

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Advances in scientific knowledge make ever more onerous the task of schools of science, medicine and social studies in keeping abreast of the needs of an age of rapid material and technical development, and in making adequate provision for advanced studies and post-graduate research.

"Science, Industry and Society,"
Editorial in *Nature*, March 27, 1937.

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SUDDEN DISTURBANCES OF THE IONOSPHERE*

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I. Introduction

THIS paper presents the conclusions and data up to the end of 1936 of a world-wide investigation, started about the middle of 1935, of a previously unknown phenomenon. The phenomenon is the occurrence of a sudden intense increase in the ionization of a region of the earth's upper atmosphere, with resultant transient disturbances in such phenomena as radio wave transmission, terrestrial magnetism, and earth currents, all simultaneous and occurring throughout the hemisphere illuminated by the sun. The radio effect is of serious practical import, as it manifests itself principally as a sudden disappearance of radio signals received on high frequencies, the period of silence ranging from a few minutes to an hour or more. The whole phenomenon is of scientific interest particularly because it appears to have its origin in sudden bursts of radiation from the sun, and is opening the way to increased understanding of the sun, the ionosphere, radio transmission, terrestrial magnetism and related phenomena.

Knowledge of this effect opens up the explanation of various partial manifestations or aspects of it in the past. Among such manifestations are undoubtedly certain recorded instances of sudden terrestrial magnetic pulses simultaneous with visible solar eruptions, reported by astronomers in the past hundred years.[1] For many years prior to 1935 interruptions of radio transmission and pulses of terrestrial magnetism had been observed which were instances of the effect described in this paper, but in each of these fields the effect was not distinguished from the many other types of vagaries that occur. Instances are given of a number of radio transmission interruptions, together with a theory partially recognizing the role of changes of atmospheric ionization, in a paper by T. L. Eckersley.[2]

In October 1935 the author reported[3] the occurrence of sudden fadeouts of radio transmission on March 20, May 12, July 6, and Aug. 30 of that year. He observed that they occurred throughout the illuminated half of the globe and not the dark half, advanced the hypothesis that they depend on some solar emanation lasting only a few minutes, and suggested observations by workers in other sciences with a view to learning of the possible occurrence of effects in terrestrial magnetism, earth currents, solar radiation, etc., simultaneous with radio fadeouts. The suggestion met with widespread interest, and evidence followed rapidly that the postulated simultaneous effects do occur.

The astronomers at Mt. Wilson Observatory of the Carnegie Institution of Washington were asked to examine their spectrohelioscopic data for the dates in question, and in November, 1935, Dr. R. S. Richardson of that Observatory informed the author that on July 6 and Aug. 30 bright eruptions had been observed on the sun within a few minutes of the times of the radio fadeouts, and on the other two dates no observa-

* This paper formed a part of the Symposium on Astrophysical Problems of the Ionosphere held in Denver, June 25, 1937. Publication approved by the Director of the National Bureau of Standards of the U. S. Department of Commerce.

[1] Instances are given in an article by G. E. Hale, Astrophys. J. **73**, 379 (1931), and in the book, *The Sun*, by C. A. Young (1884).

[2] T. L. Eckersley, Proc. Inst. Elec. Eng. (London) **67**, 992 (1929).

[3] See first two references in Sec. VIII, Bibliography.

tions had been made at the times of the fadeouts. These results were announced by Dr. Richardson and the author at the end of 1935.

At about the end of 1935 the magnetograms of the Cheltenham, Md., Observatory of the U. S. Coast and Geodetic Survey were examined by the author for the times of all the fadeouts then known, and for several of them small abrupt pulses were found, beginning at a time within two minutes of the radio fadeout time. Also, Mr. H. H. Beverage of RCA Communications Inc. reported to the author the occurrence of a large sharp pulse on an earth-current recorder within a few minutes of the time of several of the radio fadeouts.

Preliminary reports of the results, and explanation in terms of ionosphere effects, were given by the author in papers presented at the Washington meeting of the American Section, International Scientific Radio Union, May 1, 1936, and at the Cleveland Convention of the Institute of Radio Engineers, May 11, 1936. A number of brief papers have been published by the author and others, giving some of the results and preliminary conclusions (see Sec. VIII, Bibliography).

The author has had the cordial collaboration of numerous individuals and organizations all over the world in the investigation of this phenomenon; the principal collaborators are listed

TABLE I. *List of times of beginning of sudden ionosphere disturbances. (R denotes radio fadeout, S=solar eruption, M=terrestrial magnetic effect.) (The times in italics indicate the more intense occurrences.)*

DATE	GMT	EFFECTS	DATE	GMT	EFFECTS	DATE	GMT	EFFECTS
1934			*1936*			*1936*		
Nov. 28	*1710*	*RSM*	May 14	1752	*R*	Aug. 4	1727	*RSM*
1935			15	0555	*RS*	5	1607	*RSM*
Jan. 25	0335	*R*	25	*1235*	*RM*	8	1725	*RS*
Mch. 20	0149	*R*	26	1130	*RS*	23	1130	*RM*
May 12	1157	*RM*	27	0353	*R*	25	*1830*	*RSM*
July 6	*1408*	*RSM*	27	2345	*R*	26	0000	*RS*
Aug. 30	2315	*RS*	28	*0340*	*R*	28	0930	*RSM*
Sept. 13	1630	*RS*	28	*0725*	*RSM*	Sept. 4	0146	*RS*
27	1248	*RSM*	28	*1403*	*R*	4	1238	*R*
29	2053	*R*	28	*1759*	*RM*	4	1714	*RM*
Oct. 24	1100	*RM*	29	1022	*R*	5	0902	*RM*
Nov. 18	1756	*R*	30	1730	*RM*	9	1424	*RS*
29	1405	*RS*	June 3	0050	*R*	13	0342	*RS*
30	1721	*RS*	3	*1635*	*RSM*	16	1735	*RM*
30	1855	*R*	3	1825	*RM*	21	*1535*	*RSM*
Dec. 16	2215	*RS*	4	0440	*R*	Nov. 4	1701	*RS*
17	1615	*RSM*	4	*1154*	*RM*	6	*1611*	*RSM*
18	0450	*R*	5	0236	*R*	7	0345	*R*
23	1735	*RS*	9	0130	*R*	7	1450	*RS*
1936			9	*1424*	*RS*	8	1816	*RSM*
Feb. 6	1520	*RM*	9	1750	*RSM*	16	1500	*RS*
8	*0130*	*R*	9	1900	*RM*	24	1712	*R*
8	1325	*RSM*	10	*2055*	*RM*	24	*1914*	*RSM*
14	*1518*	*RSM*	11	0625	*R*	26	0900	*R*
16	1550	*RS*	11	1230	*R*	26	*1750*	*RSM*
Mch. 4	1956	*RM*	16	*1330*	*RS*	27	1651	*RSM*
10	0540	*R*	16	1715	*R*	28	1505	*R*
23	1545	*RSM*	16	*1800*	*RSM*	29	1547	*RS*
Ap. 1	0930	*RS*	17	0722	*RS*	30	1235	*R*
1	1200	*R*	17	0908	*R*	Dec. 3	1210	*RS*
2	0405	*R*	17	1248	*R*	9	1320	*R*
6	*1355*	*RM*	19	*0910*	*RS*	21	1820	*RM*
7	0230	*RS*	19	1620	*RSM*	22	1304	*R*
8	0920	*RSM*	19	1733	*RS*	24	2202	*RS*
8	1450	*RM*	19	1938	*RS*	24	2348	*RSM*
8	*1645*	*RSM*	25	1040	*RS*	26	1938	*R*
9	1320	*RS*	25	1115	*RS*	28	1058	*R*
25	1427	*RS*	July 1	0133	*R*	29	0830	*R*
25	1653	*RSM*	15	1325	*RSM*	30	0851	*R*
30	0950	*R*	30	1337	*R*	30	1031	*RS*
May 8	2020	*RM*	31	0015	*RS*	30	1100	*RS*

below in Sec. VII, Acknowledgments. Out of this work has come a body of data on 118 abrupt disturbances of the ionosphere known to have occurred from Nov. 28, 1934, to the end of 1936. A summary of the data and an explanation of the phenomenon are presented in this paper.

II. Data

In this section a very condensed summary of the available data is presented. In Sections III, IV, and V the facts regarding particular aspects of the data are presented and discussed. In Section VI is given a discussion and explanation of the entire phenomenon.

The data considered in this paper are given in extremely compressed form in Table I.[4]

It would be quite impracticable to tell the whole story of each of the occurrences. The complete details would occupy hundreds of pages. Thus in the case of numerous publications listed in Section VIII the entire article is devoted to observations at a single place of a single one of these occurrences.

Even though they represent very extensive observations, the data we have do not give comprehensive information on the occurrences. Many of them were reported from dozens of different places, but in some cases we have knowledge of the disturbance from only two places of observation (and effects reported from only one place are included in two or three cases, where radio waves were received over numerous paths and the effects were extremely intense and clearly authentic). It would be desirable that we have for each occurrence information from numerous points all over the world, on the effects which occurred in radio transmission, terrestrial magnetism, and earth currents. In no case have we such complete information, and in many cases we also lack certainty as to whether a solar eruption occurred at the time. The incomplete character of our knowledge should be remembered in interpreting the data.

On account of the necessity of compressing the data into a table of reasonable length, the times given in Table I are in most cases averages. The individual times averaged are, however, in agreement in almost all cases within two or three minutes for the radio effects and within five minutes for the magnetic effects.

The data on the radio effects are based on: (*a*) experiences of operators receiving radio signals; (*b*) graphical records from field-intensity recorders; (*c*) observations of echo signal pulses from the ionosphere; (*d*) results of radio atmospherics recording as published by R. Bureau.

A few typical radio fadeouts as recorded graphically are shown in Figs. 1 to 8. Note the sudden drop of intensity and the subsequent gradual rise. As observed by a radio operator, a fadeout is the sudden disappearance of the signals from distant high frequency transmitting stations. In most instances the intensity of the received signal was reduced to zero, but in some it merely sank to an intensity so low as to be unreadable. Whenever echo-signal pulses were being transmitted at the time of the fadeout in a given locality, the ionosphere echoes weakened or disappeared. This also is illustrated in Figs. 1 to 8. The instances of these phenomena given in these eight figures are illustrative of many thousands of observations for which the author has data on file.

The terrestrial magnetic effect listed in Table I means an abrupt change in one or more of the terrestrial magnetic elements, *viz.*, horizontal intensity, vertical intensity, and declination, usually in all three. Some typical examples are shown in Figs. 1 to 8. Most of the data on terrestrial magnetic effects were obtained from the magnetograms of the Cheltenham, Md., Observatory of the U. S. Coast and Geodetic Survey, supplemented in some cases by information from other magnetic observatories, particularly the Mt. Wilson, California, Observatory of the Carnegie Institution. On numerous occasions earth-current pulses were reported as simultaneous with the terrestrial magnetic changes; these were not separately indicated in Table I, since earth currents and terrestrial magnetism are so closely interrelated that very probably earth-current effects occurred whenever there were perturbations of terrestrial magnetism. A comprehensive examination of the terrestrial magnetic and earth-current records from all observatories has not been made, so

[4] They are given more fully in the author's complete paper published in the August number, National Bur. Stand. J. Research **19**, 111 (1937) and also in the October number of the Proceedings of the Institute of Radio Engineers.

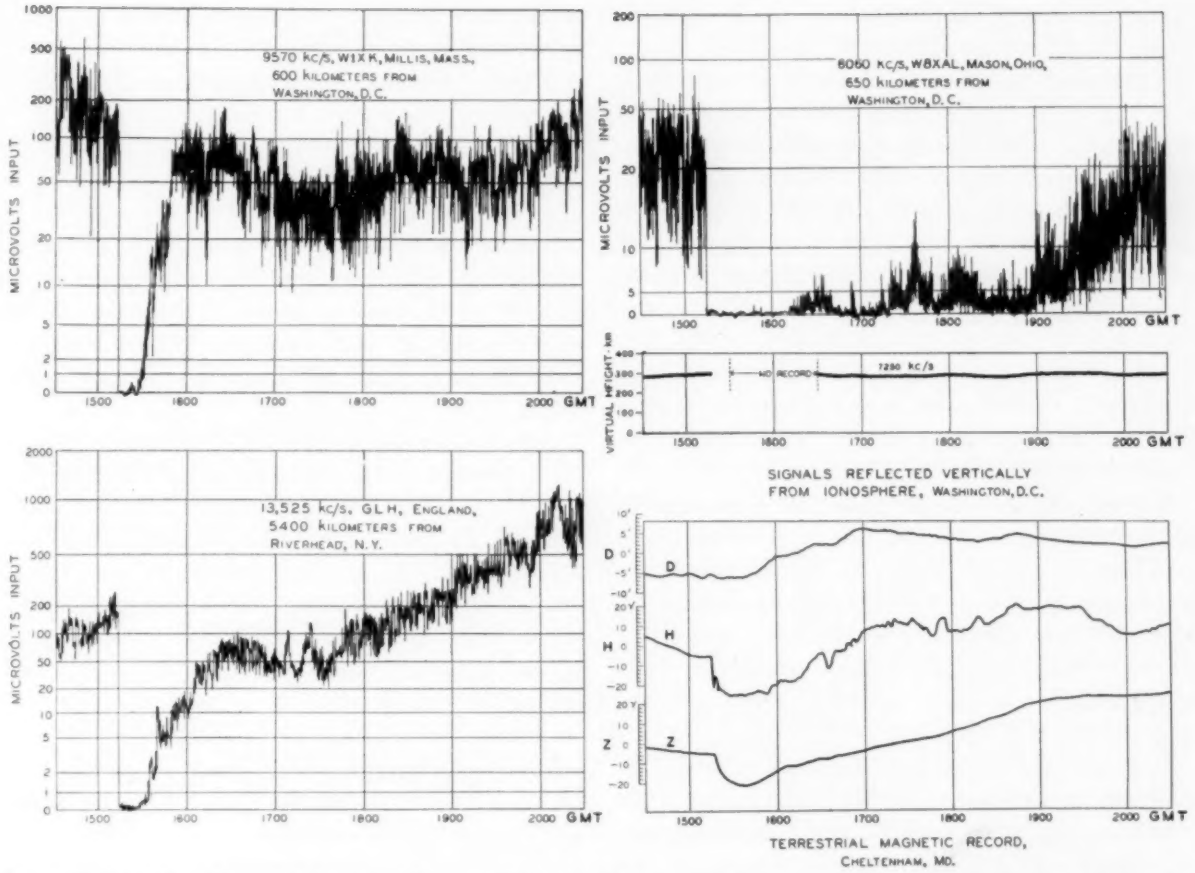

FIG. 1. Sudden disturbance of the ionosphere on Feb. 14, 1936, as revealed by radio fadeout and terrestrial magnetic perturbation.

these data, like all the others, are decidedly incomplete.

The information on the times of the solar eruptions coincident with the other effects was obtained from the *Bulletin for Character Figures of Solar Phenomena*, published in Zurich, Switzerland, under the auspices of the International Astronomical Union, supplemented by data from Dr. R. S. Richardson of Mt. Wilson Observatory from the Huancayo Observatory of the Carnegie Institution, and from R. R. McMath of Pontiac, Michigan. The solar eruptions were not so closely simultaneous as the other effects; see Sec. V, 1, below.

III. Characteristics of the Radio Transmission Effects

In this section the known facts regarding the effects of the sudden ionosphere disturbances upon radio transmission are summarized. Explanation and theory are given in Sec. VI.

Radio transmission is subject to so many vagaries that it is not surprising that the existence of this particular type of vagary was not recognized until the present investigation. The various vagaries cause large fluctuations in the field intensity received at a distance. These vagaries include such things as: fading, abrupt change of general level of intensity due to change of transmission from one ionosphere layer to another, disappearance or appearance of signals because of change of critical frequency at sunrise or other time of day, and change associated with magnetic storms, in addition to the "fadeout," which term is here reserved for the relatively sudden radio effect of the type described in this paper. Each of these kinds of vagary may produce marked diminution of received intensity of radio waves, and in the past they have not been clearly differentiated. A major result of the present research is the demonstration that the fadeout

has a number of characteristics which marks it off as a distinct phenomenon.

The data here presented have to do essentially with relatively high frequencies, i.e., above about 1500 kc/sec. There is no clear-cut knowledge in regard to effects at lower frequencies. The limited information on this is mentioned below under "Frequencies affected." Ordinarily the intensities of the waves received from radio stations on frequencies below about 1500 kc/sec. are not perceptibly affected during a fadeout. The outstanding and definite effect of a sudden ionosphere disturbance on radio transmission is thus the fadeout observed on frequencies over about 1500 kc/sec.

The fadeouts are characterized by simultaneity of beginning at all places affected, suddenness, very great change of intensity, differing duration and intensity change on differing frequencies and over paths of different lengths, maximum effect where the sun's radiation is perpendicular, and zero effect for all-dark paths. Details of these characteristics follow.

1. *Geographic simultaneity.*—Leaving aside the question of simultaneity of the radio fadeouts with other phenomena (solar, etc.), a distinguishing characteristic of the radio fadeout is the simultaneity of its beginning at the various places where it is observed. It is likely that every fadeout began simultaneously within 3 minutes everywhere, and in many cases the simultaneity was doubtless well within 1 minute.

The time of ending of a fadeout, on the other hand, is very different at different radiofrequencies, at different distances between transmitter and receiver, and in different parts of the earth; this is discussed further under "Frequencies affected" and "Geographic distribution" below.

2. *Suddenness.*—The suddenness of the radio fadeouts has astonished many radio observers, operators, and amateurs. Radio signals being received at normal intensity suddenly begin to diminish and the intensity falls to zero, usually within a minute. The effect is on some occasions preceded by a short period of unusually violent fading, echoes, and noise (of a type different from atmospherics), but the effect usually comes without warning. There is sometimes also a period of violent fading, echoes, and noise (different from atmospherics) after as well as before a fadeout.

The suddenness of commencement of a fadeout is vividly illustrated by numerous reports in which the observer stated he thought that the power had gone off in the receiving station, or that a fuse had blown, or that the stations to which he was listening had stopped transmitting, or that his receiving apparatus had developed a sudden fault. Many an observer has dissected his receiving equipment on such occasions in the vain effort to determine why it suddenly went dead.

As may be seen from the examples in Figs. 1 to 8, the received radio wave intensity drops from full value to zero, in most cases, within a minute. In some of the more intense fadeouts, like that of Feb. 14, 1936, shown in Fig. 1, the cut-off occurs within a few seconds. The duration of the effect is greater for the lower frequencies of the frequency range affected; this is discussed further below under "Frequencies affected." Sometimes the drop to zero is not quite so sudden for the higher frequencies as for the lower; this is illustrated in Fig. 6 (Nov. 6, 1936) and Fig. 8 (Nov. 24, 1936). In a few rare cases, such as the extra fadeout at 1715, Nov. 24, 1936, shown in Fig. 8, the drop to zero was gradual, lasting 10 minutes or so; such a case was not one of the more intense fadeouts, and was not accompanied by a terrestrial magnetic effect.

3. *Degree of intensity change.*—The sudden change of intensity in a fadeout is very great. In most fadeouts, there is a certain band of radiofrequencies throughout which the intensity drops from normal value to zero. Sometimes the intensity does not drop all the way to zero for the higher frequencies; see for example Fig. 7 (Nov. 8, 1936). There is evidence that there is often a frequency limit above which radio transmission is merely weakened rather than reduced to zero, and sometimes a still higher limit above which radio transmission intensity is not perceptibly reduced.

The sudden reduction of the intensity to zero when a fadeout occurs is an extraordinary experience. Not only does the radio station appear to stop transmitting, but in the more intense fadeouts even the background noise due to atmospheric ("static") disappears. The impres-

sion of the observer is that reception goes dead. This enhances the effect of the suddenness of the fadeout.

4. *Frequencies affected.*—The data on radio fadeouts indicate that they occur on all the high frequencies used for long-distance radio work, i.e., from about 1500 to 30,000 kc/sec. Reports are available on radio reception at lower frequencies during many of the fadeouts, and in nearly all cases they indicate that reception was not affected. Some automatic records made by the National Bureau of Standards indicated that the sky wave, at broadcast frequencies, was weakened during a fadeout. As the ground wave plays a large part in daytime transmission at broadcast and lower frequencies, and the ground wave is unaffected by ionosphere phenomena, fadeout effects would not be prominent and would tend to escape notice. In a very few cases there have been reports of a changed character of fading on broadcast or lower frequencies, or of an increase of intensity on the lower frequencies. Dr. R. Bureau, of France, has found that recorders of atmospherics on frequencies between 27 and 40 kc/sec. show an increase in numbers of atmospherics pulses recorded during many of the fadeouts.

For the frequency range in which fadeout effects are conspicuous, i.e., from about 1500 to 30,000 kc/sec., the effects are greater on the lower frequencies. This is true in regard to the duration of the effects and the degree of intensity change. The variation of intensity change with frequency is described in the section just above

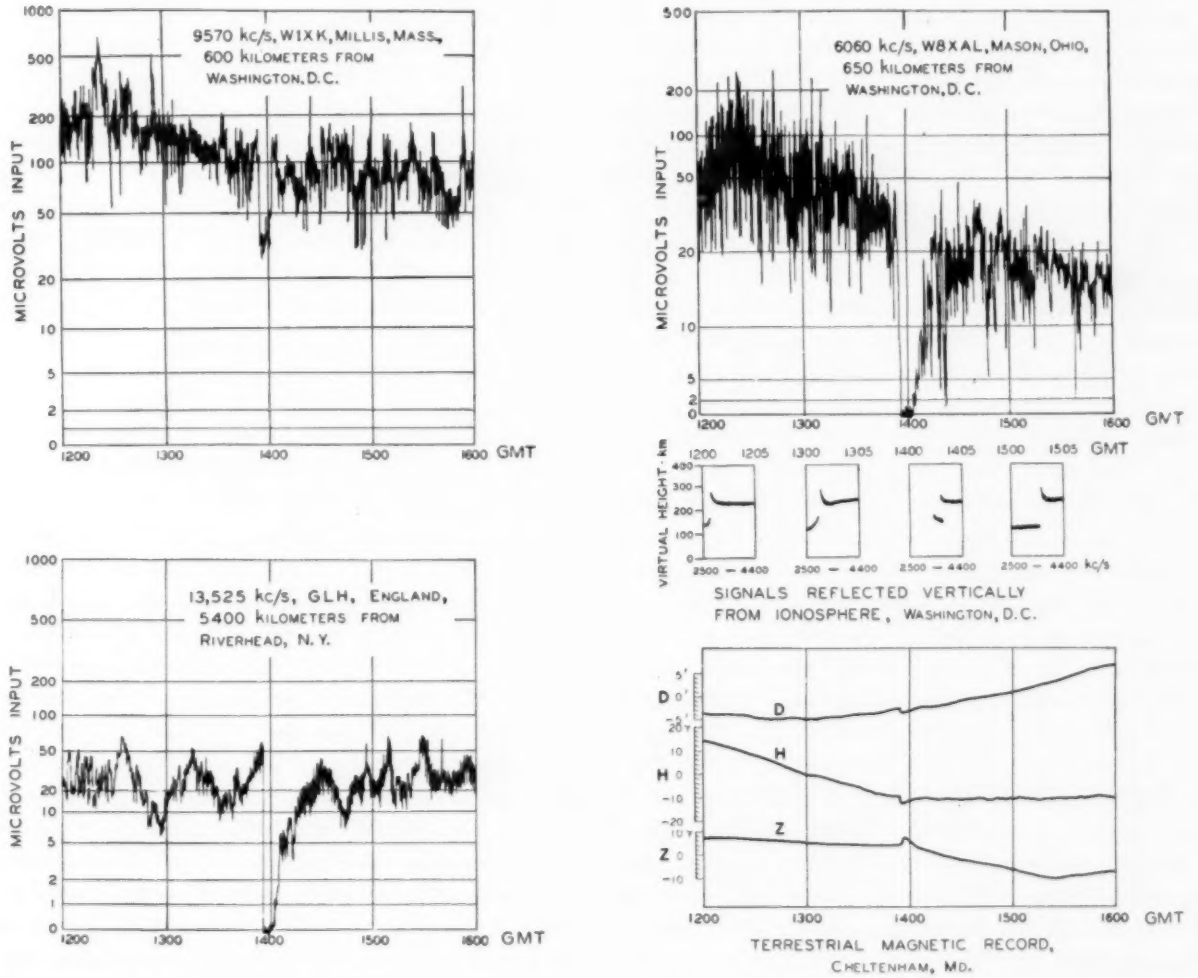
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FIG. 2. Sudden disturbance of the ionosphere on April 6, 1936, as revealed by radio fadeout and terrestrial magnetic perturbation.

on "Degree of intensity change." The variation of a fadeout with frequency is illustrated in Figs. 1 to 8.

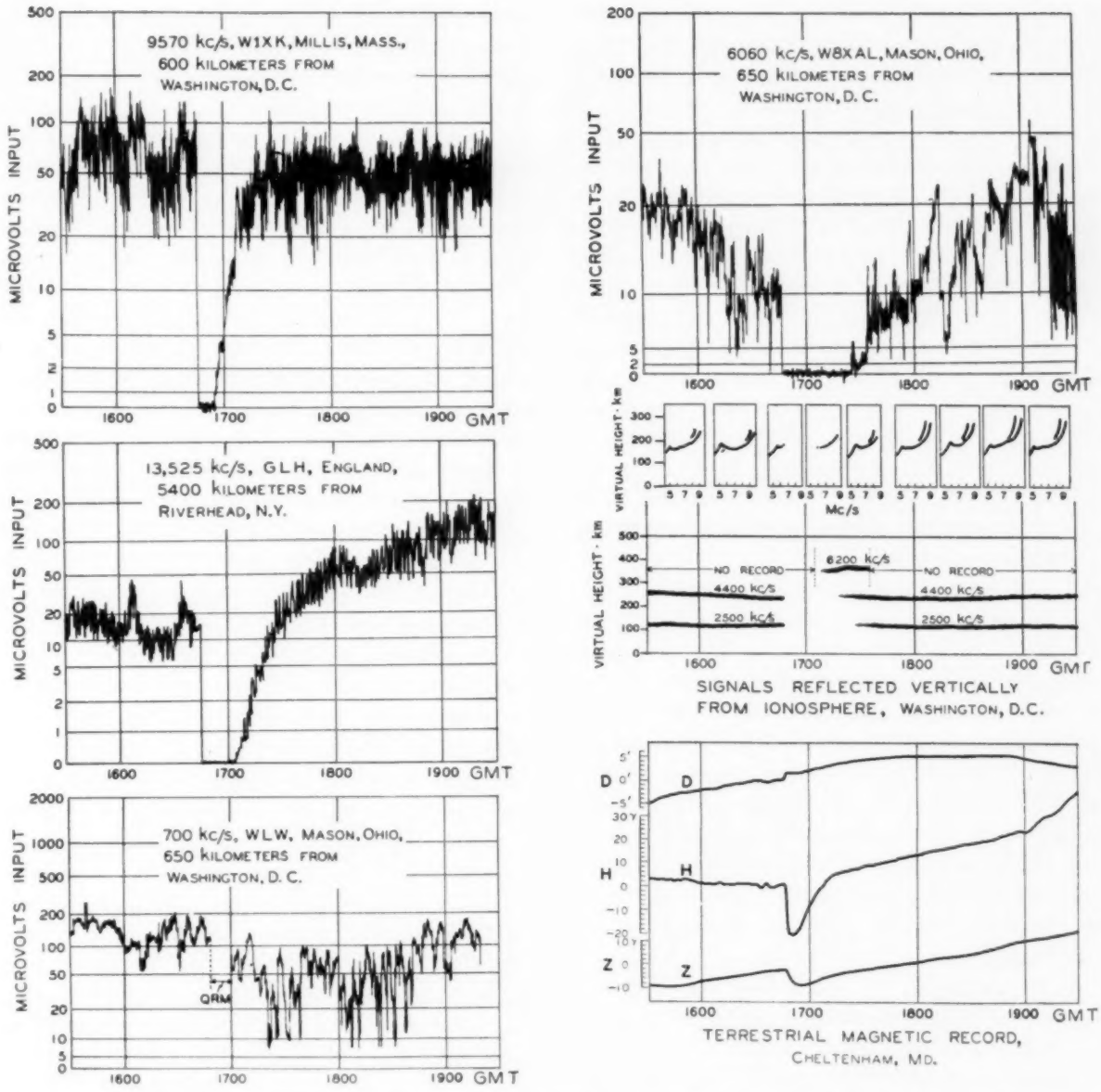
As shown in the figures, the beginning of a fadeout is simultaneous on all frequencies. This simulteneity is exact in most cases, and where not exact the times of beginning seldom differ more than two or three minutes and the effect occurs first on the lower frequencies. As also shown conspicuously in the figures, the duration or time of ending of a fadeout is very different on different frequencies. The time during which the received intensity is zero, and the time of recovery to normal intensity, are both greater the lower the frequency, other factors being the same. Interpretation of the variation of the effect with frequency in particular cases is complicated by the variation of the effect (discussed in next section below) with geographic location of the radio transmission paths affected, and also by the variation with distance of transmission. Since in long-distance transmission the waves travel a much longer path through the lower ionosphere the effects are greater for long distances than for short distances. Thus a fadeout for a long-distance transmission path, on a given frequency, will have a greater reduction of intensity and a greater duration than for a short-distance transmission path. Expressed otherwise, the fadeout effects for a long-distance path correspond to those at a lower frequency for a short-distance path. Bearing this in mind, the variation of fadeout effects with frequency is consistent in the figures and in all known fadeouts. H. A. G. Hess reported that during the intense fadeout of Nov. 6, 1936, which happened to occur during a time when long-distance transmission on 40,000 kc/sec. was possible, there was no diminution in transatlantic reception on about that frequency. This fadeout was not as intense as some others.

It is found, and it is consistent with the foregoing conclusion, that fadeouts which last longer are usually observed up to higher frequencies than those of shorter duration; where the duration is short, the higher frequencies are less affected. This is illustrated by a comparison of Fig. 1 and Fig. 7.

5. *Geographic distribution.*—All the fadeouts known to date, listed in Table I, have the characteristic discovered by the author in 1935 for the fadeouts then known, that they occur throughout the hemisphere illuminated by the sun and not in the dark hemisphere. More precisely stated, whenever a radio fadeout occurs some part of the radio transmission path is in the daylight hemisphere. The continuous automatic recorders of the National Bureau of Standards, recording the field intensities of domestic stations and the normal-incidence ionosphere reflections, have detected no fadeouts between sunset and sunrise. Since many other observers throughout the world have been watching for the effects, the lack of any reports whatever of disturbances on all-dark paths may be taken as proof of their non-occurrence. For many of the times when radio fadeouts were reported, there have also been specific reports from the dark hemisphere that radio transmission was unaffected. Sometimes a fadeout is reported as observed at a place where it is dark, but in every case the fadeout occurs only on radio transmission paths which are partly in the hemisphere illuminated by the sun. Thus, fadeouts have in a few cases been observed at midnight in certain places, without violating this principle. Conspicuous examples are: Argentina, 0400 April 2, 1936; California, 0728 May 28, 1936; England, 0016 July 31, 1936.

A study has been made to determine more specifically the variation of intensity of the effect with latitude, longitude, and direction. It is found that the effects are most pronounced in localities where the sun's radiation is perpendicular to the earth's surface. Thus they are most intense in the equatorial regions and diminish with increasing latitude. Similarly, they are most intense at longitudes where it is noon and diminish in both directions toward longitudes where it is night. These relations are true in respect to the suddenness of beginning of the radio fadeout, the time it lasts, the upper limit of frequency affected, and the degree of reduction of intensity. A fadeout which, at the place where the sun's radiation is perpendicular, may be very intense and prolonged, may, for the same frequency, be a mere brief reduction of intensity near the boundary of the illuminated hemisphere.

Variations with direction have not been completely analyzed, but they appear to be con-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700 kc/s, WLW, MASON, OHIO, 650 KILOMETERS FROM WASHINGTON, D. C.
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MICROVOLTS INPUT
1600 1700 1800 1900 GMT
6060 kc/s, W8XAL, MASON, OHIO, 650 KILOMETERS FROM WASHINGTON, D. C.
VIRTUAL HEIGHT - km
Mc/s
NO RECORD
6200 kc/s
4400 kc/s
2500 kc/s
SIGNALS REFLECTED VERTICALLY FROM IONOSPHERE, WASHINGTON, D.C.
D
H
Z
TERRESTRIAL MAGNETIC RECORD, CHELTENHAM, MD.

FIG. 3. Sudden disturbance of the ionosphere on April 8, 1936, as revealed by radio fadeout and terrestrial magnetic perturbation.

sistent with the foregoing relations. For example, at receiving points in the United States, reception from stations in the southern hemisphere usually exhibit greater effects than reception from other directions (because of passing the equatorial regions). Similarly, a disturbance occurring in the morning usually exhibits greater effects in reception from the east than from the west, and *vice versa* for the afternoon (becauses of passing the region where it is noon).

Interpretation of particular cases is complicated by the variation of the effect with the radiofrequency and distance.

IV. Characteristics of the Terrestrial Magnetic and Earth-Current Effects

In this section the known facts regarding the effects of the sudden ionosphere disturbances upon terrestrial magnetism and earth currents are summarized. The phenomena are explained in Sec. VI.

In many respects the terrestrial magnetic and

earth-current effects have the same characteristics as the radio transmission effects. These similar characteristics include geographic simultaneity, suddenness, limitation of occurrence to the illuminated hemisphere, and the same variation of intensity of effect with latitude and longitude. They are similar also in being only one among the many types of vagaries of terrestrial magnetism and earth currents. These vagaries include such things as diurnal and seasonal variations, irregular fluctuations, and magnetic storms (i.e., times of violent magnetic fluctuation). Also, as in radio, the effects due to the sudden ionosphere disturbances have in the past not been recognized as something different from the other classes of vagaries; this study has shown that they have characteristics which mark them off as a distinct and separate type of magnetic perturbation.

1. *Limitation to illuminated hemisphere.*—The data on terrestrial magnetism in the table (in Sec. II above) are based principally on the magnetograms of the Cheltenham, Md., Observatory of the U. S. Coast and Geodetic Survey. These magnetograms were examined for the times of all the radio fadeouts. In a few cases data were available from the records of other observatories. In the more intense fadeouts, magnetic effects occurred simultaneously everywhere throughout the sun-illuminated hemisphere. In all of them, no effects are known to have occurred in the dark hemisphere.

2. *Simultaneity with radio fadeouts.*—Typical examples of the terrestrial magnetic effects are shown in Figs. 1 to 8, in which a few Cheltenham magnetograms are reproduced. The magnetic pulses, when they occur, are simultaneous with the radio effects, indicating that both are manifestations of an ionosphere change. As indicated in Table I, the magnetic pulses occurred during many of the radio fadeouts but not all. The suddenness and the duration of the pulses may be judged from the figures.

3. *Geographic distribution.*—The geographic distribution of intensity of the terrestrial magnetic effects is, so far as the limited data indicate, the same as for the radio fadeouts. That is, they are most pronounced in the vicinity of that region of the earth's surface to which the sun's radiation is perpendicular, and diminish to zero at the boundary of the illuminated hemisphere. Thus the effects are greatest at low latitudes, and at longitudes where it is noon. They do not occur in the night hemisphere.

4. *Comparison with magnetic storms.*—The geographic distribution of intensity of the effects is strikingly different from that of terrestrial magnetic and earth-current effects hitherto known. For example, a world-wide magnetic storm is characterized by a "sudden commencement," a pulse which is simultaneous over the whole earth. The magnetic storms and their sudden commencements thus differ markedly from the magnetic effects associated with sudden ionosphere disturbances in respect to distribution in longitude, since the latter occur only in the sun-illuminated hemisphere.

The two phenomena differ even more extraordinarily in respect to their distribution in latitude. Magnetic storms have minimum effects at the equator and maximum effects near the magnetic poles, just the opposite of the effects of sudden ionosphere disturbances. An interesting consequence of this is that the magnetic and earth-current pulses due to the sudden ionosphere disturbances are much more striking when observed in equatorial regions than in high latitudes. They may be of the same order of magnitude as the fluctuations due to magnetic storms in equatorial regions, relatively small in middle latitudes, and negligible in high latitudes.

Besides these differences in the geographic distribution of the effects, magnetic storms and the sudden ionosphere disturbances differ in duration, the former lasting hours or days instead of the brief period of the latter.

A study has been made to determine whether there is any relation between times of occurrence of magnetic storms and the sudden ionosphere disturbances. None has been found, and the occurrence of each is quite random with respect to the other. Sudden ionosphere disturbances usually occur during magnetically quiet times, but some have occurred during magnetic storms. In studying this subject, caution should be observed to consider the results observed at a number of different locations in order to be sure that an apparent effect of the sudden type really is one. Observations of the effect at a single

location are often hard to distinguish from other types of vagaries.

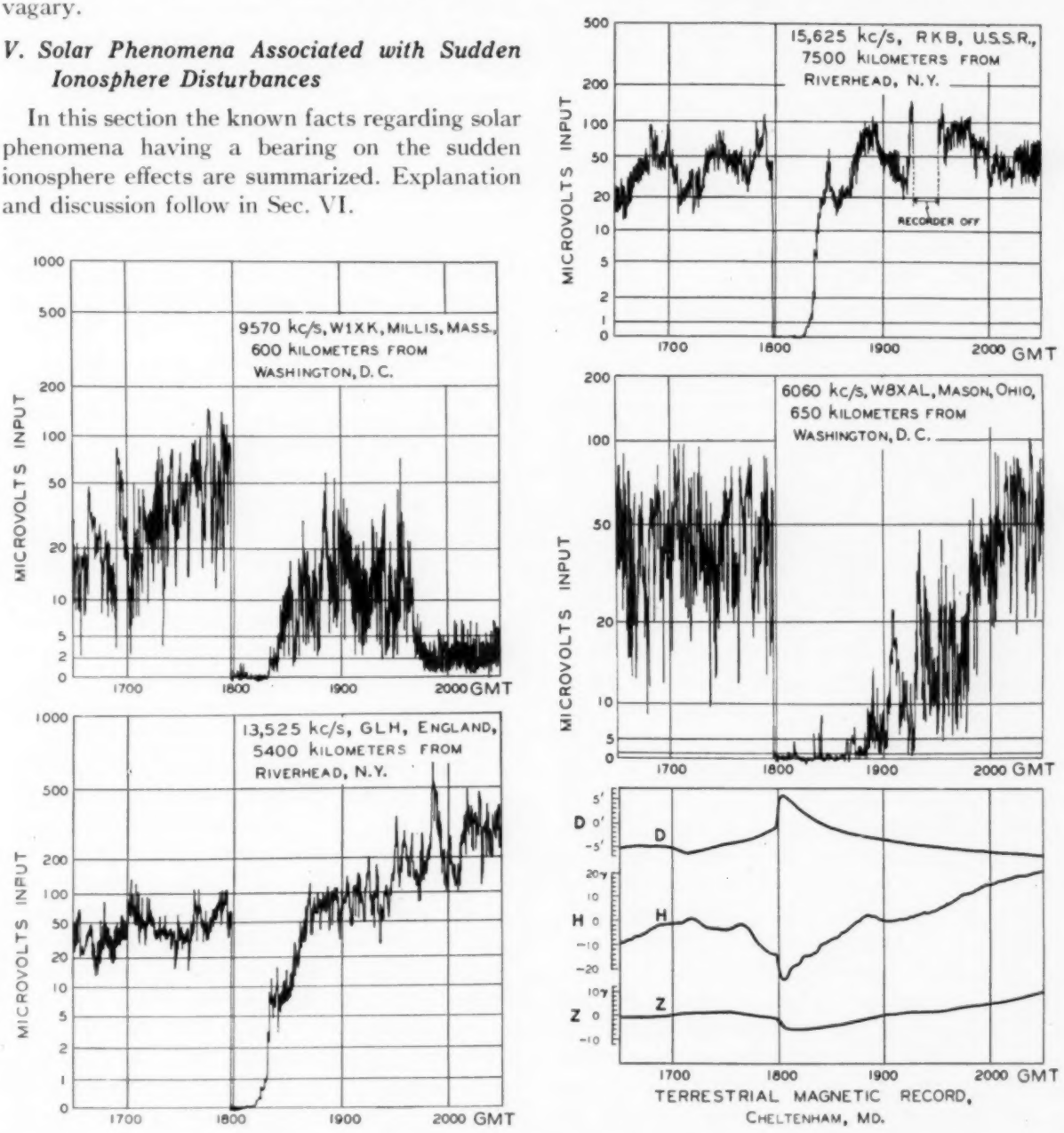
One of the major results of this research is the discovery of a separate type of terrestrial magnetic disturbance, with remarkable characteristics which clearly differentiate it from magnetic storms or any previously known types of magnetic perturbations. This is analogous to the discovery of the fadeout as a distinct type of radio vagary.

V. Solar Phenomena Associated with Sudden Ionosphere Disturbances

In this section the known facts regarding solar phenomena having a bearing on the sudden ionosphere effects are summarized. Explanation and discussion follow in Sec. VI.

1. *Exactness of simultaneity.*—The solar eruptions listed in Table I (in Sec. II above) were simultaneous in the sense that the reported time of the solar eruption overlapped the time of the sudden ionosphere disturbance.

The times stated for the solar eruptions are in most cases uncertain by many minutes. This is because of difficulties in their observation. They are sometimes seen with difficulty, and the


9570 kc/s, W1XK, MILLIS, MASS., 600 KILOMETERS FROM WASHINGTON, D. C.
MICROVOLTS INPUT
1700
1800
1900
2000 GMT
13,525 kc/s, GLH, ENGLAND, 5400 KILOMETERS FROM RIVERHEAD, N.Y.
15,625 kc/s, RKB, U.S.S.R., 7500 KILOMETERS FROM RIVERHEAD, N.Y.
RECORDER OFF
6060 kc/s, W8XAL, MASON, OHIO, 650 KILOMETERS FROM WASHINGTON, D. C.
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TERRESTRIAL MAGNETIC RECORD, CHELTENHAM, MD.

FIG. 4. Sudden disturbance of the ionosphere on May 28, 1936, as revealed by radio fadeout and terrestrial magnetic perturbation.

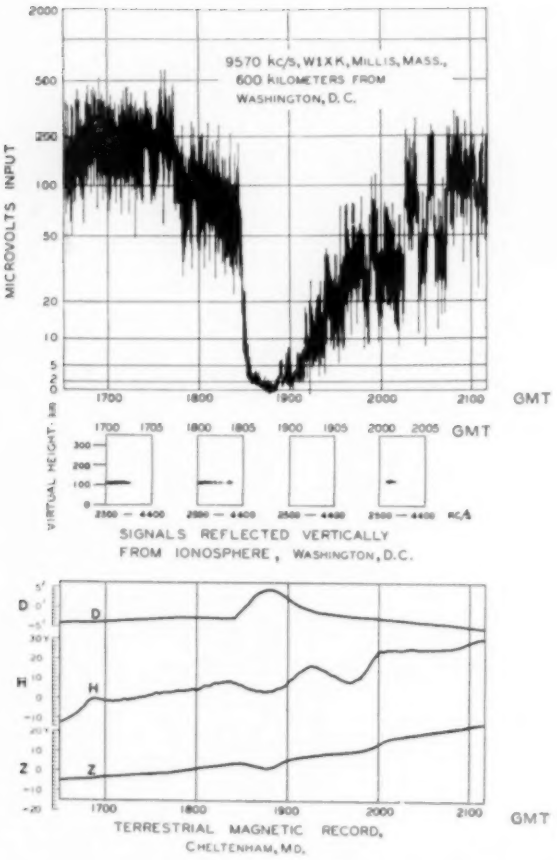


FIG. 5. Sudden disturbance of the ionosphere on Aug. 25, 1936, as revealed by radio fadeout and terrestrial magnetic perturbation.

observing astronomer cannot be sure when a solar disturbance begins or ends. They are often obtained by photographs which may be taken at intervals of 15 minutes or more, so that the time of a phenomenon indicated by a difference between two successive photographs may be uncertain.

Because of the uncertainties of their observational material, different astronomers adopt different criteria. The conditions of seeing (presence of haze, etc.) are also different at different observatories at any one time. It results that different solar observers differ considerably in the times they report for the beginning and end of solar eruptions. For example, the solar eruption of Aug. 5 listed in the table was reported by Mt. Wilson Observatory as ending at 1613 and by Zurich Observatory as ending at 1648. As another example, the eruption listed for Aug. 28 was reported by Zurich Observatory as ending at 1030, and was reported by Greenwich Observatory as still in progress at 1130. Likewise, an eruption was reported by Zurich Observatory as having been begun on July 4, 1936, at 1655, and the same eruption was reported by Mt. Wilson Observatory as having begun at 1707. These cases were all major eruptions, more easily visible than most solar eruptions. It is evidently impossible to determine the times of solar changes within a small number of minutes.

The lack of precision of the solar data thus makes it impossible to say how close is the correspondence of times of the solar eruptions and the terrestrial effects. All of the cases listed in the table may reasonably be described as simultaneous occurrences within the limits of our knowledge.

2. *Proportionate number of simultaneous occurrences.*—Of the 118 ionosphere disturbances listed in Table I, 59 (exactly half) are shown to have been coincident in time with solar eruptions. There may have been a much larger proportion than shown. The sun is not under continuous observation and hence it is not known whether a visible solar eruption occurred or not at the time of any ionosphere disturbance for which no solar eruption is reported. Most solar observatories have in the past carried on observations for not more than an hour each day. An arrangement is in effect by which observatories in different parts of the world stagger their times of observation with a view to a continuous watch on the sun. Cloudy weather and other conditions, however, prevent the full attainment of this program.

On the other hand, however, when we examine the solar records (in the *Bulletin for Character Figures of Solar Phenomena*), we find that many solar eruptions occur when no ionosphere disturbances are known to have occurred. For example, from January to June, 1936, the abovementioned bulletin lists 302 solar eruptions, and only 29 of these were simultaneous with known disturbances of the ionosphere. A larger proportion of coincidences is found if we consider only the more intense solar eruptions (those of arbitrary intensities 2 or 3); there were in the same period 69 of these listed, of which 17 were simultaneous with known disturbances of the ionosphere. It is probable that many of the visible

solar eruptions were not accompanied by detectable ionosphere disturbances, though the converse may not be true. The use of automatic radio and magnetic recorders continuously has assured knowledge of the occurrence of practically all ionosphere disturbances in the western hemisphere.

3. *Character of eruptions.*—The eruptions here discussed are bright chromosphere eruptions. They are visible as sudden increases of brightness of large bright patches on the sun's surface, and when occurring at the limb of the sun are seen as eruptive prominences. An eruption usually, but not always, takes place near an active sun-spot group. Most of the eruptions simultaneous with sudden disturbances of the ionosphere are much brighter than the average.

4. *Location of eruptions on sun.*—It is of interest to know whether the eruptions causing sudden ionosphere disturbances occur wholly or predominantly at any particular location on the sun's surface. It might be thought, for instance, that the radiation would be effective only when projected radially from the sun to the earth, i.e., when the eruptive area is in the center of the sun's disk. The solar locality of all the visually observed eruptions simultaneous with sudden ionosphere disturbances is known, and has been examined in this connection. It is found to be random, which means that the eruptions send out their radiations in all directions from the sun's surface; the terrestrial effects occur regardless of where the eruption takes place, near the sun's limb, at or near the center of the disk, or anywhere between.

The locations of the eruptive areas on the sun have also been examined to find out whether particular areas give rise to repeated effects, and especially whether such effects are repeated after one or more rotations of the sun. On a number of occasions, successive eruptions from a given solar area, accompanying sudden ionosphere disturbances, have occurred in the course of a day or two. Little evidence however has been found of any repetition of eruptions from a particular area after one or more rotations of the sun.

5. *Recurrence tendency.*—A possible periodic tendency in the times of occurrence of the sudden ionosphere disturbance was suggested by the occurrence of the ones first known to the author, and listed first in Table I, at intervals of approximately 55 days. This is shown graphically in Fig. 9, in which all the occurrences are plotted. The intensity of each occurrence was weighted on an arbitrary basis, having regard to the duration and magnitude of the effect, the number of places from which reported, etc. The intensities thus weighted by two persons independently agreed very well and were plotted as ordinates on an arbitrary scale in Fig. 9. The abscissas are time, each horizontal line being an interval of 55 days. In Fig. 10 is plotted an average curve for all the 55-day periods. The existence of a 55-day recurrence tendency is indicated. This should not be taken as proved, as two years is not considered to be a sufficient time to establish such a tendency with certainty. It may be mentioned that the 55-day recurrence tendency remains very marked even if the first seven cycles, in which it is so pronounced, be disregarded. Further analysis has indicated that the recurrence tendency averages slightly less than 55 days, but is closer to 55 than 54.

It is of interest that there is no indication of a recurrence tendency of the order of 27 days. The sun rotates on its axis in a remarkable way, rotating faster at the equator than elsewhere. The rotation period is about 24 days at the sun's equator and about 36 days near its poles. The average rotation period of the portion of the sun in which the eruptions take place, and also, incidentally, the period for which terrestrial magnetic disturbances show a recurrence tendency (presumably dependent upon some unidentified type of solar eruptions), is between 27 and 28 days. Thus the tendency to a recurrence period of 55 days, of the ionosphere disturbances, is twice the well-known solar period of approximately 27 days. Again, caution should be observed in any conclusions from this, being based on data of only two years.

6. *Relation to sun-spot numbers.*—In a general way, solar eruptions tend to be more prevalent in years when sun-spots are more numerous, and thus their number may be expected to wax and wane in an 11-year cycle with the sun-spots. There is no evidence, however, of any short time correlation with numbers of sun-spots of the sudden ionosphere disturbances or the particular solar eruptions accompanying them. The number

of these certainly does not vary from day to day, or from month to month, in accordance with the number of sun-spots. Data are not available over a long enough time to permit a conclusion as to whether there is any correlation of yearly averages.

VI. Discussion and Explanation

The foregoing facts clearly outline a phenomenon which is some type of sudden change somewhere in the ionosphere. Whenever the phenomenon occurs, it is most intense in that region of the earth where the sun's radiation is perpendicular and diminishes to zero at the outer edge of the illuminated hemisphere. Its onset usually occurs within a minute, and is simultaneous throughout the hemisphere affected. Its various effects begin simultaneously, and last from about ten minutes to several hours, the occurrences of greater intensity in general producing effects of longer duration. The effects include the sudden blotting out of high frequency radio sky-wave transmission, sudden changes in low frequency atmospherics, sudden changes in terrestrial magnetic intensities, and sudden changes in earth currents. The effects are markedly different from other types of changes in these quantities. They are more intense where it is noon than other times of day, and are more intense in equatorial regions than in higher latitudes. The radio effects are very large, indicating that the ionosphere changes producing them are intense ones.

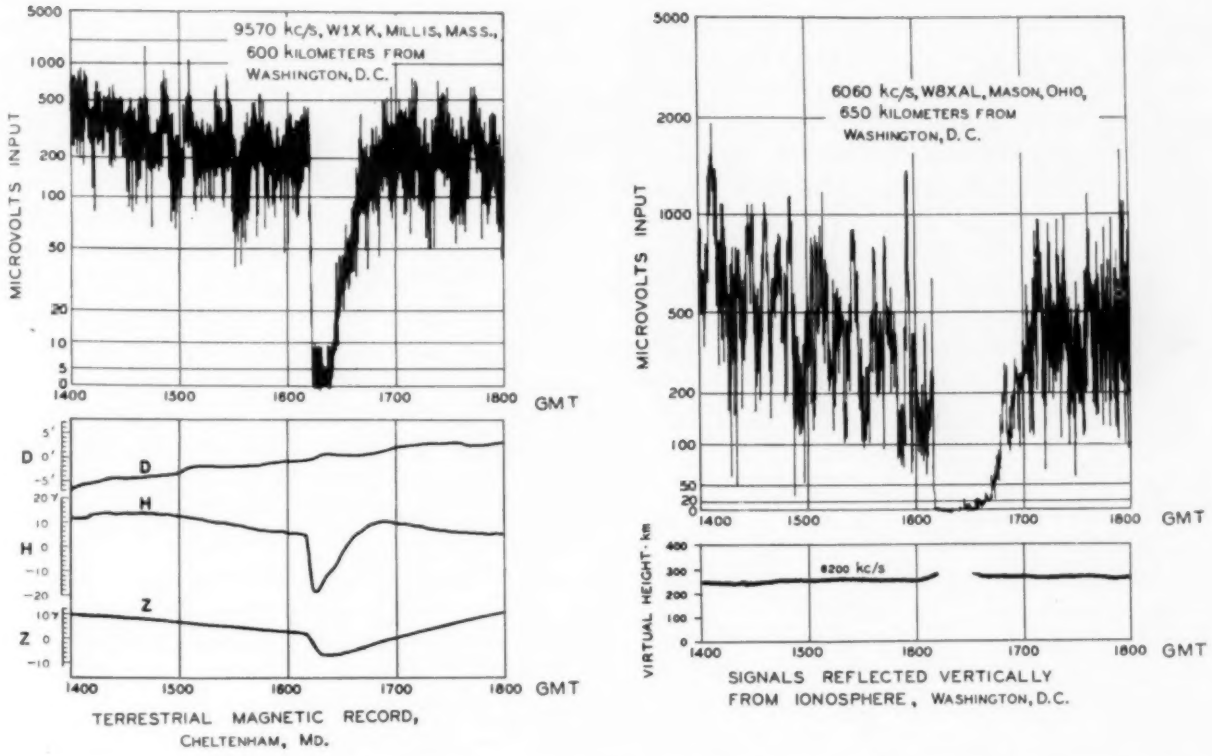
1. *Seat of the disturbances deduced from radio effects.*—The various characteristics of the effects summarized in the preceding paragraph and detailed earlier in the paper indicate them to be due to an ionosphere phenomenon; and the nature of that phenomenon is more particularly elucidated by a consideration of the radio effects.

Long-distance radio transmission takes place by means of so-called sky-waves which are reflected back to earth from the ionized upper portion of the atmosphere, or ionosphere. The ionization is stratified in the daytime into a number of layers, of which three principal layers are well recognized; the E layer, F_1 layer, and F_2 layer. The E and F_1 layers are, respectively, about 120 and 220 kilometers above the earth's surface, and the F_2 layer is at a height varying from about 250 to 400 kilometers at different times. The ionization density is progressively greater in the higher layers. The presence of ionized particles of air makes the layers reflect radio waves which reach them. For a given ionization density and angle of incidence, all radio waves up to a certain frequency are reflected and waves of higher frequency pass through to higher layers. For example, at a given time and angle of incidence, all radio-frequencies up to 9000 kc/sec. might be reflected by the E layer, those from 9000 to 12,000 kc/sec. be reflected from the F_1 layer, those from 12,000 to 30,000 kc/sec. be reflected from the F_2 layer, and no frequencies above 30,000 kc/sec. be reflected at all (i.e., no frequencies above this limit could be received over the distance considered).

An increase in the ionization of a layer raises the upper limit of frequency of radio waves which it can reflect. During a number of the sudden ionosphere disturbances measurements or recordings were in progress to determine this upper limit of frequency for the several layers, E, F_1, and F_2. In no case was there an appreciable change during or just after the disturbance. (It is possible to speak of radio observations being in progress during a fadeout because there were always some frequencies, distances, or locations for which radio transmission continued while for others the radio transmission was annihilated—see Sec. III.) It may be concluded that the sudden ionosphere disturbances do not change the ionization of the E, F_1, or F_2 layers.

On the other hand, ionosphere studies have amply proved that an increase in the ionization of a region *through* which radio waves pass on the way to being reflected by a higher layer causes an increase in absorption of the radio waves' energy and results in a diminution of the received wave intensity. This is exactly what happens, and indeed to a striking degree, during one of the sudden disturbances.

It may therefore be concluded that these sudden disturbances involve a sudden great increase of ionization in some region through which radio waves pass on the way to being reflected by a higher region. Since the fadeout occurs in radio waves reflected by the E as well as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6060 kc/s, W8XAL, MASON, OHIO, 650 KILOMETERS FROM WASHINGTON, D.C.
VIRTUAL HEIGHT - KM
6200 kc/s
SIGNALS REFLECTED VERTICALLY FROM IONOSPHERE, WASHINGTON, D.C.

FIG. 6. Sudden disturbance of the ionosphere on Nov. 6, 1936, as revealed by radio fadeout and terrestrial magnetic perturbation.

the higher layers, the absorbing medium must be below the E layer.

The seat of the sudden large increase of ionization is thus below the E layer, i.e., lower than 120 kilometers above the earth's surface. The E layer is thus not the lowest part of the ionosphere. This is in harmony with some other facts which have been discovered recently. It is now known that waves of broadcast and lower frequencies are propagated in the daytime at certain seasons by reflection from a layer lower than the E layer. This was discovered[5] by observation of the changes in the characteristics of received waves near sunset and sunrise, showing a change from E layer at night to a lower layer in the daytime and back to the E layer at night.

This low layer may perhaps be called the D layer, but not enough is yet known about it to be sure that this designation is appropriate. There may be several layers acting, whose combined effect we observe, or one or another of them may predominate at different times. Or the effective layer may more or less merge into the E layer. With our present limited knowledge it is perhaps well to think tentatively of a single low layer or region in which low frequency transmission takes place, and in which the sudden ionosphere disturbances occur.

For low frequencies (below about 1500 kc/sec.), a sudden ionosphere disturbance does not produce a fadeout because radio waves are reflected by, instead of passing through, the layer in which the sudden increase of ionization occurs. The sudden increase of ionization may even tend to increase rather than decrease the low frequency radio wave intensity; this is in harmony with the results of R. Bureau on low frequency atmospherics.

For frequencies above about 1500 kc/sec., the ionization of the low layer is ordinarily not great enough to reflect the waves. They pass through and are reflected from the E or higher layers where the ionization density is greater. When the sudden increase of ionization in the low layer occurs, however, the ionization suddenly becomes great enough to produce large absorption of the

[5] "Critical frequencies of low ionosphere layers," by N. Smith and S. S. Kirby, Phys. Rev. **51**, 890 (1937).

radio wave energy and a fadeout occurs. There is less interchange of energy between the ions and the radio waves, the higher the frequency, and therefore for very high frequencies the fadeout effects are less pronounced; this is in accordance with experience, as described in Sec. III and illustrated in Figs. 1 to 8. It is also clear from this conception why the effects on a given frequency for normal-incidence transmission are the same as the effects on a much higher frequency for grazing incidence transmission: the waves at grazing incidence travel a much longer path through the abnormally ionized layer and thus experience an added amount of energy interchange with the ions, thus compensating for their higher frequency.

The source of the sudden ionization changes must be outside the earth, and therefore has to come through the E, F_1 and F_2 layers. It must have a character, therefore, distinctly different from the source of ionization of those layers. It produces its effect at a level where the air density is great enough to insure numerous collisions of moving ions and hence rapid absorption of the radio wave energy. The radiation producing this effect is therefore of a type which can penetrate these layers and produce ionization where the mean free path is shorter, than that which produces the normal ionization in the ionosphere. The effect must be produced by a very sudden burst of very penetrating radiation, which reaches and ionizes a level of the atmosphere where the air density is great enough to insure rapid recombination of the ions as well as rapid absorption of the energy of radio waves reaching such region. This explains the great reduction of the radio wave intensity and the short duration of the effect, as well as the suddenness of the drop of radio intensity.

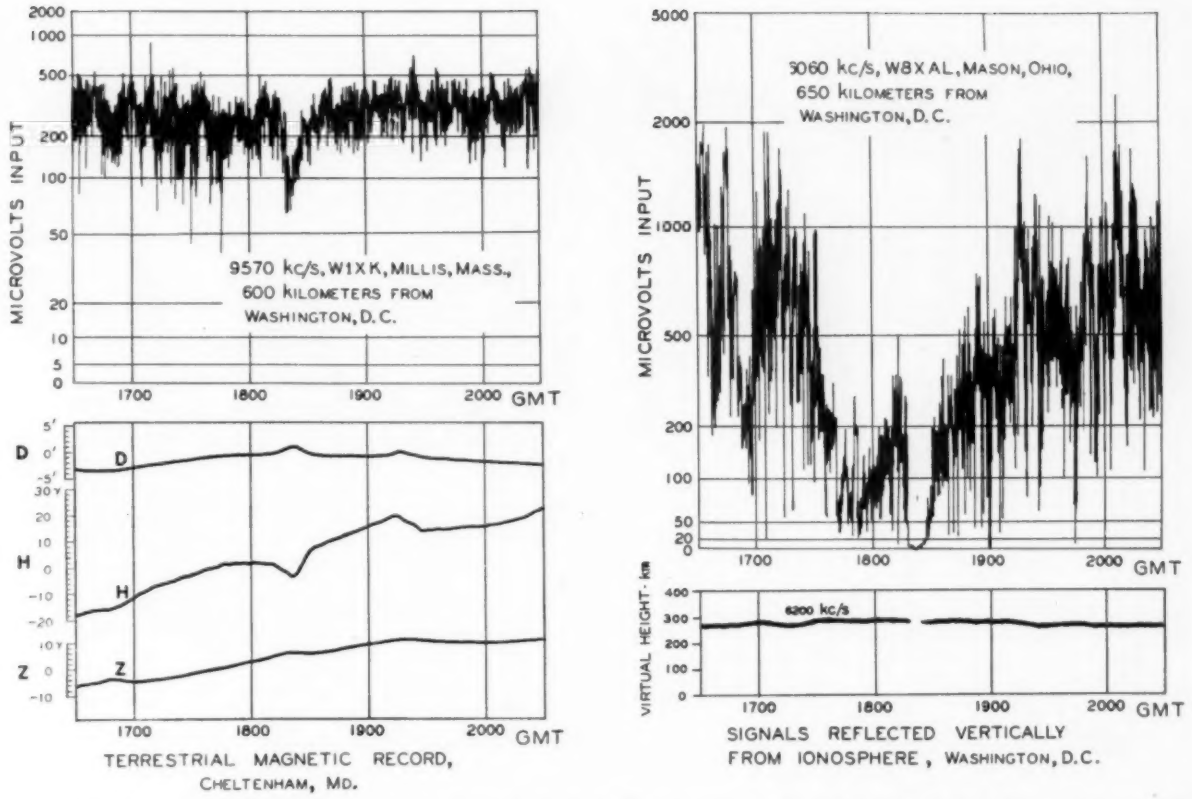
The recombination proceeds so fast that the ionization and the ionizing energy are probably very nearly in equilibrium at all times. As the ionizing radiation from the sun dies out, in accordance with the disappearance of the solar eruption, the intense ionization in the lower ionosphere wanes, and the highest radiofrequencies affected are soon freed of its effects. As the ionization diminishes, lower and lower frequencies recover from the effects. The duration of a fadeout at a given frequency is probably dependent not only on the intensity of the burst of ionizing energy but also on the duration of the solar eruption.

2. *Magnetic effects.*—The occurrence of the sudden ionization being thus inferred and explained from the radio effects, it is clear why simultaneous changes are sometimes observed in terrestrial magnetism and earth currents. Both of the latter phenomena are due in part to the motion or drift of ions in the earth's atmosphere, constituting in the aggregate vast currents whose associated magnetic field constitutes a portion of the earth's magnetism and whose fluctuations account for the variations in terrestrial magnetism and earth currents. When a sudden ionosphere disturbance of the type here considered takes place, the sudden increase in ionization permits a simultaneous sudden change in net current flowing and thus perturbations in terrestrial magnetism and earth currents. It is to be noted that such perturbations do not depend directly on the amount of the ionization, as do the radio effects, but involve also drift or motion of the ions. The radio effects are therefore not always accompanied by magnetic and earth-current perturbations. Whether the latter become observable or not depends on the complicated circumstances of the earth's magnetism at various places and times. When observed, they share the characteristics of the radio effects and the acting cause in the ionosphere, i.e., simultaneity throughout the portion of the earth affected, absence in the dark hemisphere, suddenness, and maximum intensity where the sun's radiation is perpendicular.

As previously stated, this type of perturbation of terrestrial magnetism and earth currents is strikingly different from the perturbations associated with "magnetic storms." Radio effects have shown that during magnetic storms the ionization density of the highest layer of the ionosphere (F_2 layer) is reduced and the ionization is diffused rather than sharply stratified. These effects thus prove that at least part of the phenomena of magnetic storms have their seat in the F_2 layer.[6]

It has here been shown, on the other hand, that the sudden ionosphere disturbances have

[6] See papers by Kirby *et al.*, Phys. Rev. **48**, 849 (1935); **50**, 258 (1936); **51**, 992 (1937).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TERRESTRIAL MAGNETIC RECORD, CHELTENHAM, MD.
9060 kc/s, W8XAL, MASON, OHIO, 650 KILOMETERS FROM WASHINGTON, D.C.
VIRTUAL HEIGHT - km
6200 kc/s
SIGNALS REFLECTED VERTICALLY FROM IONOSPHERE, WASHINGTON, D.C.

FIG. 7. Sudden disturbance of the ionosphere on Nov. 8, 1936, as revealed by radio fadeout and terrestrial magnetic perturbation.

their seat below the *E* layer, and the phenomena causing the terrestrial-magnetic and earth-current perturbations associated therewith must therefore also have their seat below the *E* layer.

Thus the two kinds of magnetic phenomena arise in entirely different portions of the ionosphere, in entirely different ways, and are probably due to ionizing agents of different characteristics. We thus have a new tool for analysis of the characteristics of terrestrial magnetism and for determination of their causes. There has hitherto been little known as to the locations of the vast ionosphere current systems which cause the fluctuations of terrestrial magnetism. The new possibility of localizing the levels in which different types of perturbations originate will aid in deciding between rival theories of terrestrial magnetism and should do much to bring to light the hitherto unknown mechanisms of terrestrial magnetic variations.

3. *Solar source.*—The sun is in an extremely turbulent state, and on it occur frequent eruptions from which are emitted radiations having a great range of wave-lengths. There is no reason to doubt that some of the radiations from some of these eruptions are the sudden bursts which cause the sudden disturbances of the ionosphere of this planet. This is strongly indicated by the numerous observations of such eruptions and ionosphere disturbances coinciding in time.

The lack of occurrence of an ionosphere disturbance during every visible solar eruption does not at all vitiate the idea of a causal relation, because many different kinds of radiation are emitted in solar eruptions and visible radiation is not the kind which affects the ionosphere. The existence of visible solar effects during the solar cataclysms which cause the ionosphere disturbances is fortuitous. The simultaneous occurrence of an ionosphere disturbance and the flare of light which makes the solar eruption visible indicates that the radiation causing the ionosphere disturbance travels to earth with the velocity of light. As shown above, the radiation which causes the sudden large increase of ionization of a low region of the ionosphere is of a very penetrating

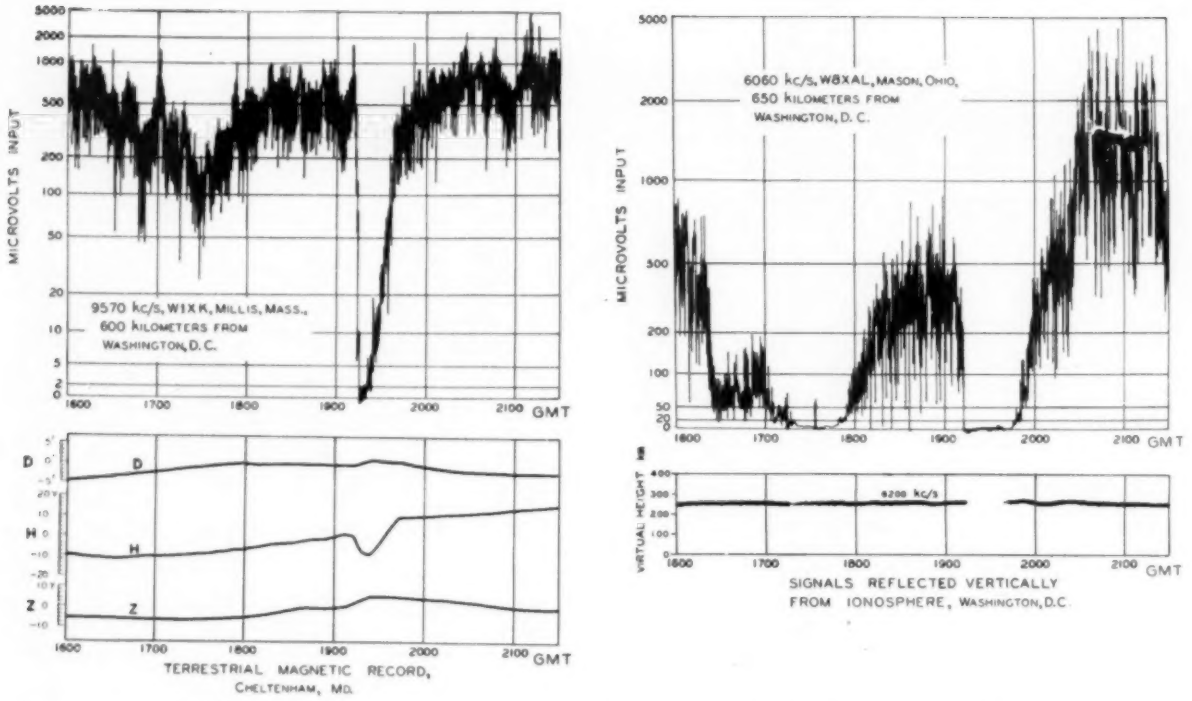

FIG. 8. Sudden disturbance of the ionosphere on Nov. 24, 1936, as revealed by radio fadeout and terrestrial magnetic perturbation. (Two fadeouts.)

type; it is therefore electromagnetic radiation of frequency far above visible light.

This doubtless gives the explanation why not all visible solar eruptions cause ionosphere disturbances. Evidently some eruptions emit the particular type of radiation which cause the sudden bursts of ionization in the earth's atmosphere, and some do not. This may be because many eruptions may rise high enough in the solar atmosphere to permit the escape of visible light but not high enough to permit the escape of the ultraviolet radiation which penetrates to the region below the E layer and ionizes it.

The ionosphere disturbances and their associated effects are the only known means of detecting the causative solar radiation, because this radiation cannot penetrate the relatively dense lower atmosphere and reach the earth's surface and thus cannot be directly detected by any instrumental means. We have thus come into possession of a means of studying a new class of invisible solar radiation, not hitherto accessible to detection or measurement.

The results of this research prove that ultraviolet light plays a role in the cause of terrestrial magnetic fluctuations, a thesis which Dr. E. O. Hulburt has presented in numerous papers in the past ten years.

Ionosphere phenomena should be of very great value in increasing our knowledge of the sun. The ionization phenomena of the F_2 layer are decidedly different from those of the E layer, and there may thus be differences in the causative radiations for the two layers. Certain effects in the F_2 layer, associated with magnetic storms, may be due to a different type of radiation. As we have seen, the radiation causing the sudden ionosphere disturbances is of still different character. All of these classes of radiation can be studied only by their ionosphere effects, as they do not penetrate down to the earth's surface. Ionosphere phenomena, as detected by radio, terrestrial magnetic, and earth-current effects thus become the unique means by which we can study various classes of radiation from the sun.

The physical nature of the sun is extremely interesting, and presents many mysteries. One of the chief mysteries is the eruptions. Little is known about the precise relation of the eruptions to sun-spots or about the cause of either. The

sun is a rotating sphere of very hot gas, and a sun-spot is a vortex resulting from a great cataclysmic change in a portion of the sun. A sun-spot lasts from a few days to a few months. The sudden eruptions, usually lasting only a few minutes, commonly occur during the early stages of a neighboring sun-spot group; they may be connected with the process which gives birth to sun-spots. This process is thought by astronomers to be the sudden formation of vast quantities of helium from hydrogen by the combination of four hydrogen atoms to form one of helium, with great energy liberation. Determination of the wave-lengths of the radiation accompanying sudden pulses occurring during this process should aid in further identifying its nature and the obscure cause within the sun. Such determination is among the possibilities of future study of the sudden ionosphere disturbances. The duration of some of the phenomena during eruptions may also be learned through this study.

Another aspect of the sudden ionosphere disturbances which is worthy of study in connection with solar phenomena is the time grouping of the disturbances. As shown in Fig. 9, the major disturbances showed a very marked 55-day recurrence tendency from Nov., 1934, to May, 1936, then in May and June, 1936, there was an extraordinary outburst of them, after which there were relatively few of them for several months. A study of the solar circumstances of the eruptions accompanying such disturbances, and the possibility of future determination of the wave-lengths of the solar radiation associated with them, may eventually elucidate the nature of the eruptive processes within the sun and the causes of sun-spots.

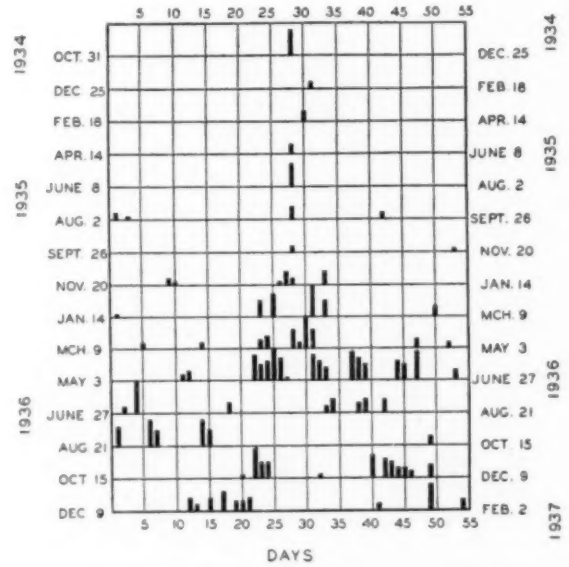

FIG. 9. Recurrence diagram of sudden ionosphere disturbances, arranged in 55-day periods; intensity of disturbance is approximately indicated by ordinate. *Note:* By error, the first six days in each line are displaced one line too high. This error in drawing does not affect the accuracy of Fig. 10.

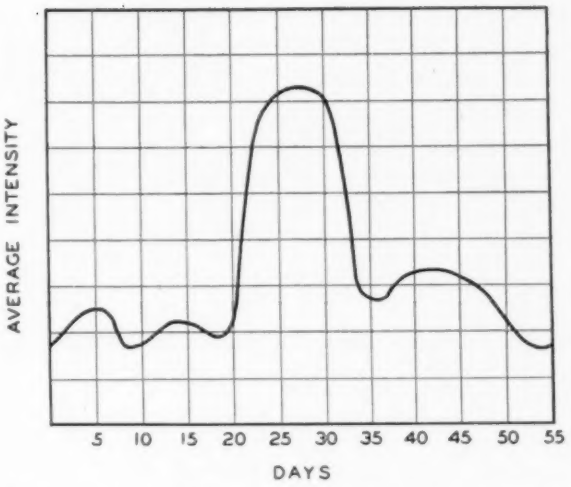

FIG. 10. The 55-day recurrence tendency, shown by smoothed average of disturbance intensity for all periods.

VII. Summary

The phenomenon described in this paper is the occurrence of a very sudden change in ionization of a portion of the ionosphere. It manifests itself by the complete fading out of high frequency radio transmission for a period of a few minutes to an hour or more, and by perturbations of terrestrial magnetism and earth currents. These occurrences are simultaneous everywhere throughout the illuminated half of the globe and nonexistent in the night half. The effect was discovered in 1935; the results of a world-wide investigation, which followed this discovery, are presented in this paper.

The radio and magnetic effects have been shown to be of a distinct type, quite different from previously known vagaries in these fields. They are of maximum intensity in that region of the earth where the sun's radiation is perpendicular.

Many of the occurrences are simultaneous with

great eruptions on the sun. Such eruptions emit vast quantities of ultraviolet light. These radiations are sometimes of such frequencies as to cause intense ionization of part of the ionosphere below the E layer. This sudden ionization causes the radio and other perturbations. Their characteristics are explained. Study of this effect is leading to new understanding of the nature of the ionosphere, the processes of radio wave transmission, the mechanisms of terrestrial magnetism, and the phenomena occurring in the sun.

VIII. Acknowledgments

The work here reported has been in large measure a world-wide cooperative study. Many individuals and organizations have sent me reports of their observations of various aspects of the sudden disturbances of the ionosphere.

The most consistent source of data has been the continuous records of field intensity of high frequency stations, and the records of ionosphere phenomena, made by my colleagues in the National Bureau of Standards, Messrs. S. S. Kirby, N. Smith, T. R. Gilliland, and S. E. Reymer.

Dr. R. Jouaust of the Laboratoire Central de Radio-électricité, France, and the author have regularly interchanged data during this study. Dr. Jouaust has compiled and distributed comprehensive bulletins of data on the radio fadeouts, principally as observed in Europe. These were forwarded from the French National Committee to the other National Committees of the International Scientific Radio Union, and this service is being continued.

The Carnegie Institution of Washington has collaborated in the supplying of solar and terrestrial magnetic data. In particular, Dr. R. S. Richardson, of the Mount Wilson Observatory, California, has cooperated with the author through the supplying of information monthly on solar eruptions.

The Coast and Geodetic Survey has assisted by supplying copies of its daily magnetograms made at its terrestrial magnetic observatory at Cheltenham, Md.

Regular reports on radio fadeouts as observed during the handling of radio communication traffic have been furnished by:

H. H. Beverage, Chief Research Engineer, RCA Communications Inc.
H. Pratt, Chief Engineer, Mackay Radio and Telegraph Co.
L. Espenschied, Bell Telephone Laboratories.
N. Koomans, Chief, Staatsberdreijf der P. T. T., Holland.
T. Nakagami, Chief Engineer, Kokusai-Denwa Kaisha Ltd., Japan.

Reports have been furnished on particular radio fadeouts and related phenomena by many others too numerous to mention. The most active of these collaborators have been:

Chief Signal Officer, War Dept., U. S. A.
Naval Communication Service, U. S. A.
Aeronautical Radio Inc., U. S. A.
British Broadcasting Corporation, England.
W. Calloway, Office of Posts and Telegraphs, Kuala Lumpur, Malaya.
J. H. McMullin, Commissioner of Police, British Col., Canada.
C. P. Edwards, Dept. of Transport, Ottawa, Canada.

Reports on numerous radio fadeouts have been supplied by many radio amateurs, forwarded through the American Radio Relay League. Of these, the reports of F. D. Jenkins of Atlanta, Ga., have been particularly helpful.

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Undergraduate curriculums in technological schools will increasingly avoid specialization except in rather general fields, and will devote increasing attention to physics, chemistry, and the general principles and methods of engineering, with supplementary education in social science and training in the art of exposition. Such broad and basic training is needed to give the vision and adaptability required for positions of responsibility in a world of activities which are increasingly dependent on applications of science in new and varied ways.

KARL T. COMPTON, "Technological Education," *The Scientific Monthly*, October, 1937.

THE NATURE OF BRIGHT CHROMOSPHERIC ERUPTIONS*

BY R. S. RICHARDSON

Mount Wilson Observatory
Carnegie Institution of Washington

BRIGHT eruptions in the chromosphere are among the most spectacular of astronomical phenomena. The amazing rapidity and magnitude of the changes involved, together with the probability that they may affect the earth, have always made them of exceptional interest to solar observers. In the latter half of the nineteenth century bright eruptions at the sun's limb were carefully studied and described by Secchi, Young, Lockyer, and others, and the fundamental importance of these early visual observations should not be overlooked in modern times.

A new era in this field of research began in 1890 with the invention of the spectroheliograph independently by Hale and Deslandres. With this instrument "the light from a spectral line of calcium, hydrogen, or other substance is singled out by a narrow second slit, which moves across the plate while the first slit moves across the solar image. A monochromatic picture is thus built up of countless narrow slit images, recorded side by side in slow succession."[1] The spectroheliogram shows the distribution over the sun's surface of the element corresponding to the particular line selected. For example, a spectroheliogram taken with the *K* line shows the disk as it appears in the light of singly-ionized calcium vapor.

Another advance was made about 1924 when Dr. Hale succeeded in constructing a spectrohelioscope, by means of which visual observations can be made of certain features both on the disk and at the limb of the sun which before could only be studied on spectroheliograms.

Observations with the spectrohelioscope are almost always made with $H\alpha$, because of the great strength of this line in a region of the spectrum to which the eye is highly sensitive. Probably for this reason, the bright eruptions have been commonly called "bright hydrogen eruptions." It should be emphasized, however, that this term is definitely misleading, for the eruptions are equally conspicuous on spectroheliograms taken with the *H* and *K* lines of calcium. They have also been observed in the D lines of sodium, the D_3 line of helium, several members of the Balmer series, the *b* lines of magnesium, and probably the infrared lines of ionized calcium. "Bright chromospheric eruptions" is a much better designation for these outbursts.

The recent discovery[2] that the bright chromospheric eruptions are apparently the direct cause of fadeouts in high frequency radio transmission has made them of interest not only to astrophysicists, but also to geophysicists and radio engineers. This interest is not confined entirely to the realm of pure science, for many of the fadeouts have seriously interfered with commercial broadcasts. As a consequence, there has been an increased demand lately for information regarding the nature of solar eruptions. Individual examples have been discussed in detail by Hale,[3] but so far as the writer is aware, there is no general account of their principal features. It is hoped that the summary given here will be of use to those whose previous work has not included the subject of sun-spot activity.

It is difficult to generalize about bright chromospheric eruptions because notable exceptions can

* This paper formed a part of the Symposium on Astrophysical Problems of the Ionosphere held in Denver, June 25, 1937.

be found to almost any statement made. Hence, the following remarks should not be considered as hard and fast rules, but more as an indication of the usual course followed in most cases.

First of all, a distinction should be made between two kinds of flocculi: quiescent and active. The former are almost always visible on spectroheliograms in the vicinity of spot-groups. Sometimes they are only a little brighter than the general background but quite often attain considerable intensity, especially over large spot-groups. But they never show any rapid changes in either form or intensity. The active type undergoes very rapid changes, and it is with this kind of flocculi that we are especially interested.

The eruptions are almost always associated with sun-spots. The brightest are generally found near large, long-lived spot-groups, particularly those with irregular magnetic polarities. The outburst usually occurs somewhere between the leading and following spots, rather than entirely in front of or behind the group. If, however, the group consists chiefly of a single large spot, the flocculi almost invariably avoid the region directly over the umbra, and appear close to one side of the penumbra. The bright eruptive material is evidently at a high level in the sun's atmosphere, for it obscures most of the photospheric detail seen on the direct photographs, and also overlies much of the fainter quiescent flocculi around the group. Direct confirmation is obtained from spectroheliograms which show bright eruptions at the sun's limb above the level of the chromosphere.

Eruptions are observed at any period in the life of a spot-group, but they appear to be most common in the earlier stages before the group consists principally of one stable spot. Although most eruptions are in the neighborhood of sun-spots, a few of great intensity have occurred in regions where no spots could be discerned.

The eruption may be so small that it can only be detected with difficulty, or it may be so large and bright that it completely dominates all other markings on the spectroheliogram. The most extraordinary feature is the rapidity with which the outburst develops. From four to ten minutes is the time required for most of them to reach maximum intensity. The interval from maximum to normal varies much more widely. In most cases the flocculus goes almost as quickly as it came; but sometimes it fades rapidly for about fifteen minutes and then diminishes very slowly, so that the region is still abnormally bright from one to six hours later. Again, a spot-group may be intermittently active, a series of six distinct eruptions having been seen in the same group within nine hours.

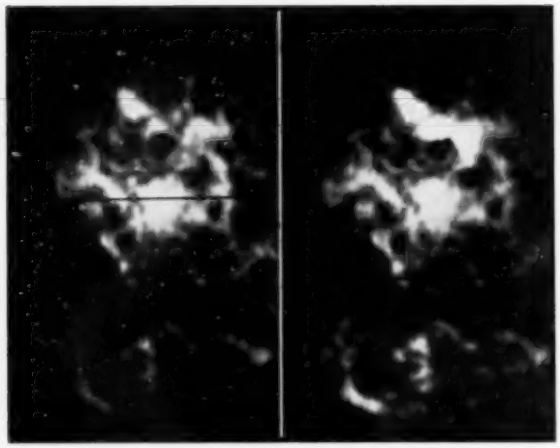
Eye-estimates of the brightness are made on a scale of 1 to 3, adopted by the International Astronomical Union. Although the estimates of different individuals frequently vary considerably, they serve as a useful indication of their relative importance. Small eruptions are by far the most numerous, and often minor changes in brightness are noticed but not considered worth including in the list sent quarterly to Meudon for publication in the *Bulletin for Character Figures of Solar Phenomena.*

Out of 164 eruptions photographed at Mount Wilson from May, 1935 to April, 1937, inclusive, 69.5 percent were of intensity 1, 23.2 percent of intensity 2, and 7.3 percent of intensity 3. Many of these eruptions were over the same spot-groups, for after allowing for recurrent spots, 751 different groups appeared during this interval, but only 82 or 11 percent were observed to be associated with bright eruptions.

The mean duration of an eruption depends roughly upon its brightness, as might be expected. Our records for the interval given above show the mean lifetime of bright eruptions of intensities 1, 2, and 3, for which both the beginning and end were observed, to be about 12, 20, and 28 minutes, respectively. If one of intensity 3 that lasted for 103 minutes is excluded, the average for the remaining eight eruptions of maximum brightness is only 19 minutes.

These results differ considerably from those given by the observers at Greenwich, namely 20, 30, and 45 minutes.[4]

Extreme care should be used in drawing conclusions about the frequency of bright eruptions, because this depends in a complicated way upon several factors, such as the number of spots on the disk, their size and age, and the length of time that they are observed. For example, from May, 1935 to May, 1936, inclusive, the sun was observed at Mount Wilson on the average for 37



(*a*) (*b*)

FIG. 1. Spectroheliograms taken in the light of calcium showing an eruption over a group of spots that occurred on May 16, 1921. Exposure *a*, taken at $16^h\,00^m$ GCT., shows the normal appearance of the spot-group. On *b*, taken 11 minutes later, a bright eruption has developed.

hours a month, and the mean daily number of spot-groups during this period was 5.6. Beginning June, 1936, the spectroheliograms were taken automatically on motion picture film throughout most of the day. As a consequence, from June, 1936 to the end of April, 1937, the sun was observed for an average of 144 hours per month. The mean daily number of spot-groups also increased to 8.8. On the assumption that the number of bright eruptions photographed is proportional to the mean daily number of spot-groups and the length of time that they are observed, we would expect to find about six times as many on our records during the second period as the first. But actually the average number observed per month increased only from 4.9 to 9.1.

Part of this discrepancy may be explained by the following considerations. If a single spectroheliogram shows no sign of eruptive flocculi, it is fairly safe to assume that there has been no activity for at least as long as the average minimum duration of a bright eruption, or for about fifteen minutes. Hence, any series of observations should be increased by this amount. When allowance is made for this extra interval that the sun is effectively under observation, the average observing time per month for the first period is increased by 30 percent, and the second period by 12 percent. But even after this correction is applied, the number of bright eruptions seen during the second period is still only one-third as great as might be expected. The reason for this probably lies in the sporadic way in which the outbursts occur, so that a fair sample is not obtained when data are available for only a few years.

There are several marked differences between spectroheliograms taken in the center of $H\alpha$, and those taken with the bright strip in the center of the broad K line of calcium (called K_2). The vortex structure which is so conspicuous around spot-groups on the hydrogen spectroheliograms is seldom seen in those taken in the K_2 line. Also the dark markings or prominences on the disk which are a notable feature of the hydrogen spectroheliograms can only be dimly discerned on the calcium plates made with K_2. But the bright eruptive flocculi are nearly identical in structure on $H\alpha$ and K_2 spectroheliograms taken a few minutes apart.

For many years the spectroheliograms at Mount Wilson were taken with two slits: one on the $H\alpha$ or K_2 line, and the other over the continuous spectrum about 250A to the violet. In this way two images of the sun were taken simultaneously: one a hydrogen or calcium spectroheliogram, and the other simply a monochromatic image resembling a direct photograph.

In the course of the routine solar observations we have secured many plates which show bright eruptions in the light of $H\alpha$ or K_2, but which are never visible on the monochromatic images taken at the same time. This indicates that the phenomenon is primarily one of line emission in the chromosphere, and that there is little or no increase in black-body radiation from the photosphere.

Not much is known as yet about the actual intensity of the eruptive flocculi. Visual measurements made at Greenwich on hydrogen flocculi give values ranging from 0.75 to 1.25 times that of the continuous spectrum near $H\alpha$. Several attempts have been made at Mount Wilson to measure the intensity of hydrogen flocculi by photographic photometry. The brightest flocculi on our calibrated plates are about 70 percent as bright as the continuous spectrum. A series of $H\alpha$ spectrograms taken in 1917 by Ferdinand Ellerman at Mount Wilson shows eruptions far

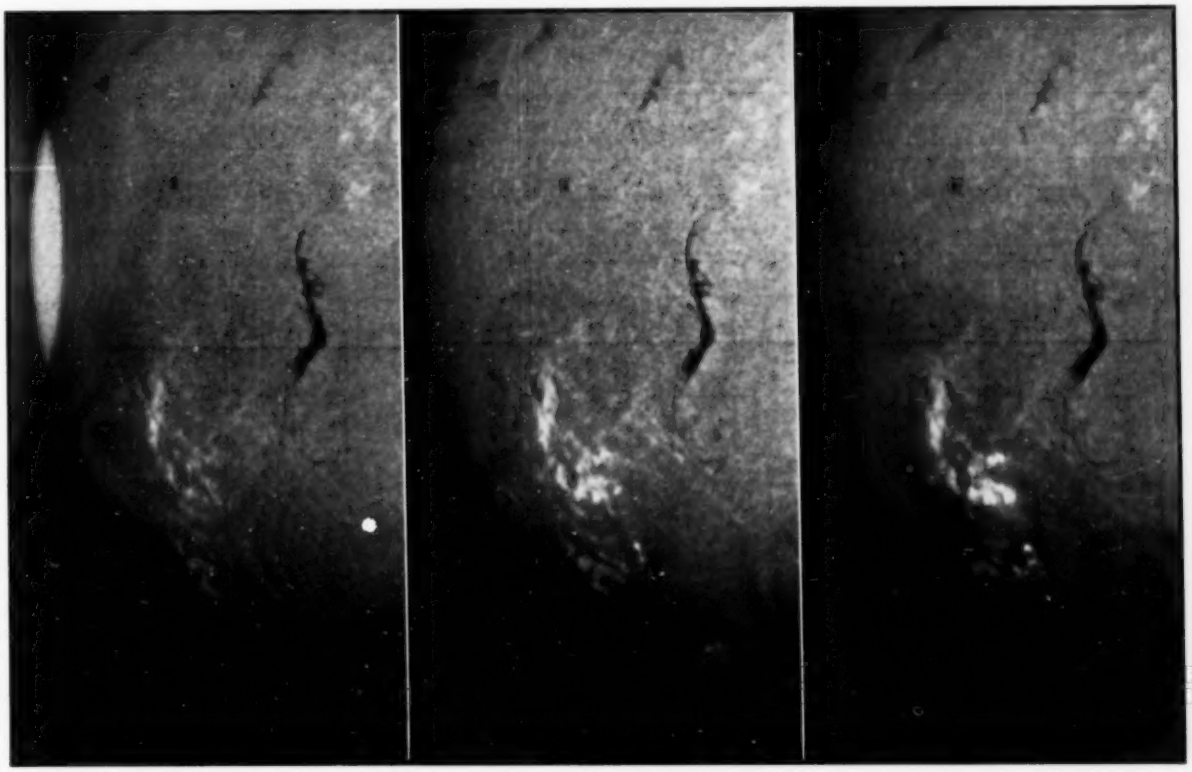
brighter than any we have taken later. The 1917 plate is not calibrated, but the continuous spectrum on adjacent exposures overlaps in several places, and the overlap is only slightly denser than the hydrogen emission. In this case, then, the flocculi were almost twice as bright as the continuous spectrum.

A remarkable feature about bright chromospheric eruptions is that they sometimes occur almost simultaneously over widely separated spot-groups. This was discovered in 1935 while making a catalogue of the hydrogen spectroheliograms taken at Mount Wilson since 1917. After the exclusion of all questionable data there still remained not only many examples of two simultaneous eruptions, but also instances in which three and even four widely separated spot-groups had erupted at about the same time.

These results were derived from a comparison of plates taken on successive days. But since June, 1936 our spectroheliograms have been taken automatically at four minute intervals throughout most of the day, and as a result our records since then are much more nearly complete. We also have several long series of exposures at brief intervals taken before June, 1936 in the study of radio fadeouts. These continuous runs have caught seven examples of eruptions occurring from two to fifty minutes apart, often in opposite hemispheres.

It is difficult to determine how many nearly simultaneous eruptions might be expected by chance, but an examination of probabilities indicates that the number would be much less than has actually been observed. The writer believes, however, that more convincing evidence is obtained simply by inspecting the plates themselves. In many cases, the effect is so striking that it is hard to doubt that the eruptions are not in some way connected.

The results suggest that bright chromospheric eruptions are evidence of some deep-seated disturbance which may manifest itself at widely separated points on the sun.



A *B* *C*

FIG. 2. A series of spectroheliograms made with the light of hydrogen, showing the development of an outburst near the limb of the sun. Exposures *A*, *B*, and *C* were taken at $16^h\ 24^m$, $16^h\ 30^m$, and $16^h\ 37^m$, respectively. The dark absorption marking nearby is a prominence on the disk.

Summary

Bright eruptions in the chromosphere have always been of exceptional interest to solar observers. A new era in this field of research began in 1890 with the invention of the spectroheliograph. Another advance was made about 1924 with the construction of the spectrohelioscope. With these instruments it is possible to observe the sun in the light of a single element only.

Recently the discovery was made that bright chromospheric eruptions are apparently the direct cause of serious and wide-spread fadeouts in high frequency radio transmission. As a result, they have become of interest to investigators whose previous work has not included solar activity. A summary is given of the principal features of importance.

The eruptions are most often seen near large, long-lived spot-groups, particularly those with irregular magnetic polarities. The bright flocculi are above the spot-group and obscure most of the photospheric detail. A few eruptions of high intensity have occurred where no spots could be discovered.

The time required for most eruptions to attain maximum intensity is from four to ten minutes. The interval from maximum to normal varies all the way from a few minutes to several hours.

Eruptions of minor importance are nearly ten times more numerous than those of maximum brightness. Only about 11 percent of all the different spot-groups observed are found to be associated with bright eruptions.

The average lifetime of outbursts observed at Mount Wilson is roughly proportional to its brightness, being about 12 minutes for faint eruptions and 28 minutes for very bright ones. These results differ considerably from those given by observations at Greenwich of 20 to 45 minutes for eruptions of corresponding intensity.

The number of eruptions observed in a given time depends upon many factors, such as the number of spots on the disk, their size and age, and the length of time that they are observed. Hence, extreme care should be used in drawing conclusions about the frequency of bright eruptions until considerable data are available for discussion.

The bright eruptive flocculi on hydrogen and calcium spectroheliograms taken a few minutes apart are nearly identical in structure.

Observations at Mount Wilson on the continuous spectrum when an eruption is known to be in progress, have never shown any increase in brightness over the active region. This indicates that the phenomenon is primarily one of line emission in the chromosphere, and that there is little or no increase in black-body radiation from the photosphere.

Visual measurements of the actual intensity of bright hydrogen flocculi made at Greenwich range from 0.75 to 1.25 times that of the continuous spectrum. An eruption of exceptional brilliance was photographed at Mount Wilson in 1917, which is probably almost twice as bright as the continuous spectrum.

A remarkable feature about bright chromospheric eruptions, is that they occasionally occur almost simultaneously over two, and sometimes even three and four, widely separated spot-groups. An examination of probabilities indicates that the number of nearly simultaneous eruptions that would be expected by chance is much less than the number actually observed.

The results suggest that bright chromospheric eruptions are evidence of some deep-seated disturbance which may manifest itself at widely separated points on the sun.

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4. H. W. Newton, B. A. A. **47**, 109 (1937).

Here and There

Symposium on Drying and Air Conditioning

The Chemical Engineering Symposium Committee of the Division of Industrial and Engineering Chemistry is actively engaged in plans for the fourth chemical engineering symposium on "Drying and Air Conditioning." The meeting will be held at the University of Pennsylvania, Philadelphia, on December 27 and 28. A number of interesting papers have been promised from industrial and educational sources covering theoretical foundations and their applications. A round-table discussion of drying equipment is expected to increase materially the practical significance of the program. Further information may be obtained from the symposium chairman, D. B. Keyes, department of chemistry, University of Illinois, Urbana, Illinois.

★

New Appointments

Dr. R. d'E. Atkinson, associate professor of physics at Rutgers University, has been appointed to a chief assistantship at the Royal Observatory, Greenwich, in succession to Dr. R. v. d. R. Woolley.

★

Dr. Dayton Ulrey, formerly manager of the physics division in the Westinghouse Research Laboratories and lecturer in physics at the University of Pittsburgh, has joined the Radiotron Division of the RCA Manufacturing Company at Harrison, New Jersey, where he will have charge of the engineering and development of power tubes for both radio and nonradio applications.

★

Dr. William J. Kroeger has been appointed instructor of physics at the University of Pittsburgh for the year 1937–1938. Prior to this Dr. Kroeger was connected with the Department of Justice, Bureau of Investigation, at Washington, D. C.

★

Dr. Gregory Wannier of Switzerland has been appointed instructor of physics at the University of Pittsburgh for the year 1937–1938. Prior to his coming to the United States, Dr. Wannier held an assistantship at the University of Geneva, Switzerland. Last year he held a Swiss-American exchange fellowship at Princeton University.

★

Dr. Henry Abraham Boorse, of the College of the City of New York has been made assistant professor of physics in Barnard College, Columbia University.

Dr. Maurice Biot of the University of Louvain has been made assistant professor of mechanics at Columbia University.

★

Mr. C. W. Williamson of Carnegie Institute of Technology has been promoted from instructor to assistant professor of physics.

★

Dr. C. E. Leberknight of Carnegie Institute of Technology has been appointed assistant professor of physics. Dr. Leberknight has been connected with Tech since 1933.

★

Mr. J. A. Ord, formerly a graduate assistant at Carnegie Institute of Technology, has been appointed as an instructor at that institution.

★

Journal of Applied Physics

For December

Superstructures, by **F. C. NIX**

Long Range Weather Forecasting, by **HURD C. WILLETT**

High Rotational Speeds, by **J. W. BEAMS**

Uses of Microfilm, by **WATSON DAVIS**

Insulator Breakdown, by **A. VON HIPPEL**

Contributed Research Papers on a Characteristic of the Copper Arc During the Formative Period, and Some Physical and Radiographic Properties of Metallic Intensifying Screens.

★

Cleans Air Electrically

One of the latest creations of the Westinghouse Research Laboratories is a commercial electrostatic air cleaner which removes about 99 percent of all particles in the air. Dust particles so small that they flow through any mechanical filter are removed in a simplified process of electric precipitation. By this process, impurities are taken from the air, not by sifting them out mechanically but charging all particles electrically and then pulling them out as they pass through an electrostatic field, in a manner similar to that by which a magnet attracts iron filings.

In the cleaning process the air is first bombarded by ions—minute electrical charges—emitted by wires as fine as human hair and which carry a charge of 12,000 volts.

The ions attach themselves to particles in the air thus giving the particles an electrical charge. Next the treated air is drawn through a series of cells consisting of alternately spaced high potential and grounded plates. By charging the high potential plates at 5000 volts an electrical field is established. As the treated air passes through these cells, the charged particles adhere to the plates and the air so freed of all solid matter passes on through ducts that lead to the areas being served by the equipment.

In the Field Building, Chicago, 18 units have been installed which are capable of cleaning 272,000 cubic feet of air each minute. In a year's time, it is estimated, the installations will have collected approximately 600 bushels of impurities, 90 percent of which will consist of particles one-hundredth the diameter of human hair. By weight, the collection will consist of one-third ash; another third fixed carbon, soot lampblack and other derivatives; and the remaining third volatile matter such as oils and greases. Sulphur, bacteria, pollen in season, and other substances found in suspension in the atmosphere of any city, are also deposited on the plates.

The precipitator consists primarily of a system of cells made up of flat aluminum plates. In each cell there are 111 plates, each eight by nine inches in size. The Chicago system includes 369 cells or 40,959 plates. The tungsten ionizing wires are but 0.005 inches in diameter and nearly half a mile of this wire is required for this installation.

★

Radiometer for Fog Signaling

Successful heavy weather signaling is now taking place with the Hayes radiometer. Long wave-length radiation penetrates foggy and thick atmosphere much better than radiation of short wave-length. The Hayes radiometer is sufficiently sensitive to detect and measure these long wave-length radiations at great distances.

★

Atom Smashing Equipment

Industrial engineers of the Westinghouse Electric and Manufacturing Company, expecting to solve some of the mysteries surrounding the structure of matter, are preparing to bombard targets of various material with submicroscopic particles shot from a gigantic "atom-smasher" at 30 million to 100 million miles an hour, according to Dr. L. W. Chubb, director of Westinghouse Research Laboratories.

Now being constructed at his company's research headquarters is a unit for conducting experiments in the field of nuclear physics. It consists of a huge pear-shaped tank, 30 feet in diameter and 47 feet high, housing an electrostatic direct-current generator and other required parts including a 40-foot vacuum tube, through which particles are shot in the bombarding of various types of targets. The structure, including a two-story building, is 65 feet high or about as tall as a six-story building.

Voltages generated in the "atom-smasher" will range to 5,000,000 and beyond. Such high voltage will accelerate particles of matter shot through the vacuum tube up to 100 million miles an hour. On their way to bombard targets at the end of the tube, the particles will be counted, measured and identified by special instruments developed for this purpose. They will emerge from the end of the vacuum tube through thin windows of metal and strike the targets with velocity great enough to penetrate the nuclei thus producing new substances.

★

Lightning Behavior

Lightning may strike a tree, travel to the ground, but if the soil happens to be of gravel or of a poor conductor type, it is liable to bounce out again and do further destructive work until it finds a ground of less resistance. This announcement was made recently by K. B. McEachron, in charge of General Electric's artificial lightning and high voltage laboratory, who has observed several occurrences of this character in connection with his recent investigation of lightning. In one of these cases, lightning came down a 90-foot pine tree and plowed up a furrow in the ground until it reached a pole supporting telephone wires. It went up the pole leaving some splintered wood behind, and finally found its ground connection after passing through the telephone wires.

In another case, in New Hampshire, lightning followed down a tree, traveled a distance of approximately 50 feet over the earth to pass up another tree, then jumped approximately one foot to a 110-volt lighting circuit, from which it dissipated itself in lightning arresters connected to the power circuit.

The three main hazards of standing under a tree during a storm are: (1) the discharge may side-flash from the tree; (2) the discharge in passing through high resistance soil at the base of the tree may pass considerable current up one leg of a person and down the other. This is often the reason why cattle are killed under trees; (3) the tree may explode and a person may be injured by the flying debris.

★

Transducer Corporation Announces Coaxial Cable

Transducer Corporation announces a new coaxial cable which has a large number of uses. Among these are antenna lead-ins; transmitting antennas, transmission lines and feeders; lines between photoelectric cells and amplifiers; measuring instruments where high frequency losses or conductivity losses must be reduced to a minimum; galvanometers and electrometers; aircraft antenna lead-ins, etc. The new product of Transducer Corporation is a flexible coaxial cable called "CO–X." This cable is reduced to its simplest components, that is, the inner conductor, a set of spacers, and the outer conductor which acts as a shield. This simplicity has been made possible by the design of the spacers and by the material used in their construction.

Columbia's Television Transmitter Nearing Completion

The Columbia Broadcasting System's new television transmitter is being given its first power tests at a Camden, New Jersey, manufacturing plant, and probably will be ready for use shortly after the first of the year. It will provide television programs from the nearby studios now being built by Columbia which may be picked up within a radius of approximately 40 miles over a total area of about 4800 square miles of thickly populated territory.

Columbia's new transmitter really consists of two complete units almost identical in construction. One of these will be used to transmit high fidelity sound while the other produces pictures exactly synchronized with that sound. Only a slight difference in design is needed to perform these different functions despite the fact that the sound transmission will cover a frequency range of up to 10,000 cycles while the wave band needed to reproduce high frequency 441 line interlaced pictures extends to the tremendous total of 2,500,000 cycles.

Twenty-four water-cooled tubes, ranging in length from ten inches to around four feet, have been especially designed for use in the two transmitters. Each of the latter has a 7500 watt output with a 30,000 watt peak modulation. Due to the fact that tremendous heat will be generated by the 400,000 watts of power consumed in producing this output, a complete air conditioning unit has been built to cool the 120 gallons of water per minute used to reduce the temperature of the vacuum tubes and other parts of the equipment. In addition, 1000 gallons of oil are needed to cool the ten gigantic transformers used.

Television cameras, which also are being given final tests at Camden, look much like those used on motion picture stages. They are mounted on counterweighted "dollies" so they can be moved about easily and raised and lowered at will. Each is connected to its control equipment by a flexible cable one and a half inch thick which contains a total of 32 circuits four of which are coaxial.

★

Scientific Forest Fire Forecasting

A scientific method of computing the daily index of fire hazard and forecasting the hazard for the next day is now in use by sixty forest stations in Quebec and New Brunswick. Known as the Wright system, the new method of forecasting forest fire hazards eliminates guesswork and individual judgment. The new system is based on daily records of rainfall, evaporation, wind and relative humidity.

Science Service, September 27, 1937

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Annual Science Exhibition

The Annual Science Exhibition held in Murat Theater in connection with the meeting of the A. A. A. S. in Indianapolis, December 27–30, will hold especial interest for physicists. Professor H. M. Randall will present an exhibit of equipment used in far infrared spectroscopy including records of automatic spectrometer recordings both with prisms and gratings. Large prisms and plates of potassium bromide and potassium iodide will be shown with photographs of the ovens used in growing crystals. Also, gratings having a surface 10×20 inches will be displayed together with photographs of the ruling engine.

Professor A. H. Compton will have a display of charts and diagrams showing compiled results in recent cosmic-ray measurements on the Pacific Ocean and at various observatories in cooperation with the Carnegie Institution of Washington. Also a new set of counting tubes for the measurement of cosmic rays underground will be shown. These large diameter tubes are about one meter long and have a counting rate of 3,000 per minute. They will be used with fourfold coincidence as developed by Volney Wilson.

Professor Harold C. Urey will place on exhibit samples of water which have an increased concentration of the O^{18} isotope approximately four and one-half times that of natural water. Also there will be very sizable samples of ammonium chloride whose nitrogen contains as high as 2.5 percent of N^{15}, being a six and one-half-fold increased concentration of this isotope. These samples have been prepared by the distillation of water and by a chemical exchange reaction between ammonium ion and ammonia gas. Diagrams will be shown illustrating the method of the researches and the progress made in using these materials.

Scientific results of observations of the total eclipse of the sun of June 8, 1937, by the National Geographic Society-U. S. Navy Expedition to Canton Island, in the mid-Pacific, and new types of equipment used by the expedition will be featured in the exhibit by the National Geographic Society. The Radio Corporation of America will have another fine display pertaining to physics in radio development. Mr. Loyd A. Jones of Eastman Kodak Company will show a film on the growth of crystals under polarized light.

★

New Booklets Received

Crystal Optics (12 pp). This booklet contains prices, sizes and specifications as to precision of workmanship and quality of crystal material for comprehensive series of windows, lenses, prisms, and achromats made of fluorite, quartz, and rocksalt for use of wave-lengths ranging from 1250A to 15 mu.

Hydron Metallic Bellows (43 pp). A catalog of the Clifford Manufacturing Company of Boston has a description of the characteristics and properties, prediction of life, assembling, soldering and cleaning of bellows, and diaphragms *vs.* bellows. Also there is an article on hydron bellows assemblies for remote control of temperatures.

Leaves (pp. 33–40). Vol. 1, No. 5, October 5, 1937. This issue contains an article on "The thickness of paint films applied with a straight-edge spreader" with illustrations of the equipment used.

Cenco News Chats (23 pp). Vol. III, No. 15, October, 1937. This issue contains articles on "Spectrometry and spectrography—a new profession" and "Control of sound in buildings as a new branch of applied physics."

Some of the New Books

Elasticity, Plasticity and Structure of Matter. R. Houwink. Pp. 376+xviii, Figs. 214, 14½×22 cm. University Press, Cambridge, and Macmillan Company, New York, 1937. Price $6.00.

This book attempts in a qualitative rather than quantitative way to describe and to analyze the "mechanical" properties of *all* known types of solid and quasi-solid substances. Through a unified treatment of this complex subject it hopes to bring into closer contact the physicist, the chemist and the scientific technologist, who, working with different methods and almost always with different aims have amassed an enormous amount of information on the elastic and plastic properties of matter.

In the first four chapters phenomenological definitions and descriptions of various types of elastic and plastic deformations are given. Yield and rupture, strain hardening, hysteresis phenomena, relaxation, thermal recovery, etc. are discussed and methods of measurement sketched. How these properties can be understood qualitatively in terms of general properties of cohesion of atoms and molecules and their thermal agitation is briefly indicated.

Chapter V on the plasticity of crystals is written by W. G. Burgers who as a specialist in this field describes the roentgenographic investigations on plastically deformed crystals and who analyzes the problem of the mechanical strength of crystals in the light of current conceptions which are based on the assumption of the existence, even in the most perfect real crystals, of various types of imperfections. In this chapter as well as in the rest of the book perhaps too little attention is given to the influence of the conditions in which solid matter is formed. One also misses the important considerations advanced by P. Duwez (Phys. Rev. **47**, 496 (1935)), on the basis of the theory of secondary structures in crystals.

Chapters 6 and 7 on amorphous substances (glass, resins, asphalt) and on rubber illustrate the influence of polymerization, gelformation, under-cooling and introduction of foreign atoms (vulcanization) on the mechanical properties.

The following five chapters on the chemical and physical properties of cellulose, proteins (muscles), bakers' dough, paints, lacquers and clay make entertaining reading and illuminate well the magnitude of the task of trying to reduce the mechanical properties of these substances to simple physical principles.

Chapter 13 on sulphur briefly discusses this instructive case of a simple element, whose ability to form several stable molecules and molecular complexes apparently is responsible for the formation of various solid modifications whose mechanical properties range from brittleness to high elasticity.

The reader who expects to find in this book a satisfactory theoretical treatment of the elasticity and plasticity of solids will be disappointed. The book, however, well describes a vast number of important phenomena and advances many suggestions which will no doubt stimulate this or that physicist, chemist or technologist to start new investigations on the mechanical properties of solids. Herein lies perhaps the greatest value of the book.

F. Zwicky
California Institute of Technology

Physics for Students of Applied Science. J. Edmond Shrader, professor of physics, Drexel Institute of Technology. Pp. 638+ix, Figs. 583, 15½×23½ cm. McGraw-Hill Book Company, New York, 1937. Price $4.00.

This text is written for "serious" introductory physics courses that are "usually given for one year of 10 to 12 semester hours." Its title will seem misleading to those who anticipate finding in it a strong emphasis upon the applications of physics, for the engineering utility of physics is not stressed, nor is the inclusion of applications noticeably more extensive than in many of our standard college texts. It presents the fundamental phenomena and principles of *classical* physics; and the extensions that might be expected in a text written primarily for students of engineering are chiefly in theory or in phenomena, rather than in practical applications.

The material included is not so advanced in character, as extensive. While quantitative treatment is not otherwise neglected, the calculus is seldom used. Definite integrals make a brief appearance in the application of Ampere's law. The phenomena of alternating current circuits are not included. The usefulness of this text is, therefore, not limited by its degree of difficulty to students in engineering, nor is it particularly adapted for use in institutions in which students in engineering are prepared to use the calculus in their general physics course.

The treatment and the sequence of presentation are conventional. Except for the somewhat brief treatment accorded gyrostats, heat engines, and thermocouples, each section is quite comprehensive. Modern developments are touched on but lightly. The treatment of the concept of potential and the chapter on wave characteristics preceding sound and light should prove helpful to students. A fairly comprehensive list of problems is found at the end of each section, and answers are given to alternate problems.

The diction is smooth and serious in style. Earnest students should like it. "No apology is offered for not making an appeal where a light treatment of the subject is desired." Critical teachers will find flaws in clarity. Some will regret the lack of emphasis on systematically isolating bodies in problems involving equilibrium and unbalanced forces; that Bernouilli's theorem is not deduced from the conservation of energy; a certain vagueness in

the attempt to differentiate potential difference and electromotive force; the omission of the neutron in discussing the structure of nuclei. This text should prove, however, a useful addition to the list of those now available.

R. A. PATTERSON
Rensselaer Polytechnic Institute

Kimball's College Textbook of Physics. Revised by Peter I. Wold, professor of physics, Union College. Fifth edition. Pp. 729+11, Figs. 585, 15×22 cm. Henry Holt and Company, New York. Price $4.00.

The first edition of Kimball's College Physics was published in 1911. At least one of the four previous editions has been used at sometime in practically all of the important colleges and universities in this country. This revised text has the following characteristics.

(1) The order in which the topics are presented, mechanics, liquids and gases, properties of matter and its internal forces, wave motion and sound, heat, magnetism, electrostatics, electrodynamics, light and modern physics is entirely conventional. The sub-topics of mechanics,—general principles, statics, kinematics and kinetics of a particle, rotation of rigid bodies and universal gravitation permit an orderly and acceptable presentation of that important subject.

(2) Semi-modern physics is discussed in the last thirty-eight pages of electrodynamics. Strictly modern physics is introduced in the last thirty pages of the book.

(3) The sub-topics within some sections have been noticeably rearranged. The section on kinematics, rotation and heat are cited as illustrative. Electricity has been largely rewritten and new material has been added to sound and modern physics. It is the opinion of the reviewer that the new arrangements have improved the teachability of the book.

(4) The problems in the text are adequate and well graded. They are interspersed in small groups through each division instead of being concentrated in large numbers at the end of the divisions. Many of the problems are new. No answers are given.

(5) The figures in the text are very interesting. Some of the old ones have been omitted, some have been redrawn and some entirely new ones have been added. The style of drawing used in the new figures is such that the new ones can be readily identified. New and old figures are sometimes found in contrast on the same page. The two figures on page 598 are a good example of this contrast.

(6) The text presumes the student will be able to use the elemental facts of trigonometry.

(7) Very liberal use is made of italics. Important words, laws, principles, summary statements and definitions are italicized. Two sizes of type are used, a standard size for the main body of the book and a smaller size for problems, summary tables, and advanced discussion which may be omitted. The new book is fifty-six pages shorter than the previous edition.

(8) The book contains many interesting tables whose usefulness would be enhanced if they were numbered and indexed.

The book contains very few innovations and departures from accepted standards. It is in no sense a survey book but a splendid text for the thoughtful student and the serious teacher.

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Der Ultraschall und seine Anwendung in Wissenschaft und Technik. L. BERGMANN. Pp. 230. V.D.I.-Verlag, G.m.b.H., Berlin, 1937. Price 18.50 gold marks.

Among our Contributors

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Dr. Wayne B. Nottingham received degrees from Purdue University of B.S. (E.E.) in '20, and E.E. in '29; and from Princeton University of A.M. in '26 and Ph.D. in '29. He was the Benjamin Franklin fellow of the American Scandinavian Foundation for studies in Physics at Uppsala University, Sweden, '20–'21; assisted in carrier telephone development at the Bell Telephone Laboratories '21–'25; was a Bartol Research Foundation fellow '26–'31; and is now an Associate Professor of Physics at the Massachusetts Institute of Technology carrying on and directing research in the general field of electronics.

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Contributed Original Research

Electrical and Luminescent Properties of Willemite Under Electron Bombardment

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An insulated surface uniformly bombarded with electrons of a given energy attains a potential relative to other elements in a high vacuum tube such that exactly as many electrons leave the surface by secondary emission as there are primary electrons arriving. A tube and circuit have been constructed for determining accurately this potential for willemite surfaces while being bombarded by electrons of energy range up to 10,000 volts. It was found that the surface potential was only slightly negative with respect to the most positive anode of the tube over the lower range of energy but finally reached an upper limit of potential relative to the cathode usually between 6000 and 7000 volts. The resistance between wires covered by the willemite was found to be independent of the bombarding current and voltage except in so far as this bombardment changed the temperature of the material. A special potassium phototube is described which was used to determine the light output from the bombarded surface as a function of the current density and the electron energy. The light was found to be accurately proportional to the current for densities below 2.5×10^{-6} amp. per sq. cm but above this a saturation effect set in quite gradually so that with a current of 20×10^{-6} amp. per sq. cm the light output was only 65 percent of the value which it would have been had the light intensity per unit current density remained constant. The light output for a constant current was found to increase with $(V-V_0)^2$ where V_0 is the "dead voltage" when the bombarding energy was less than that required to penetrate through the individual grains of the willemite. An experimental nine-inch cathode-ray tube was also studied for screen potential and light output as a function of current density and anode voltage. The difference in potential between the screen and the anode was again small for the lower range in voltage but with anode voltages above 7000 volts, the apparent screen potential depended on the current density so that a change of potential of the screen of as much as 1500 volts was observed as the current density was increased from one to ten milliamperes per sq. cm. The light output increased with the square of the bombarding potential up to 1500 volts but above this it increased with the 1.2 power of the voltage. The light output per unit current density observed at 10^{-2} amp. per sq. cm was only two percent of that observed at 10^{-6} amp. per sq. cm on account of the severe "saturation" effect found at high current densities.

INTRODUCTION

MATERIALS which luminesce under electron bombardment have been used in "electron projection" tubes by Johnson and Shockley[1] and others to study the electron emission from hot filaments by accelerating the electrons from the filament to a coaxial glass cylinder coated internally with a luminescent substance. In order to make these thermionic studies more quantitative, we needed to know more about the electrical and luminescent properties of the phosphors used and therefore undertook what was originally intended to be a brief investigation along this line. The results obtained seem to be of sufficient general interest to warrant their publication in spite of the fact that the tube design would have to be improved before one could maintain that the results were entirely free from possible adverse criticism. Since it would require a longer time to make the necessary improvements than there will be available to the writer in the near future, it has been thought best to bring forward the results which are available to date with the hope that the work will be extended and made more quantitative in this laboratory or some other.

[1] R. P. Johnson and W. Shockley, Phys. Rev. **49**, 436 (1936).

OBJECTIVES

It is obvious that the potential of a phosphor, when under electron bombardment, will adjust

itself relative to the other elements of the tube so that there will be no accumulation of charge. If the phosphor is entirely insulated, either secondary electron emission or the arrival of positive ions or both of these processes must be invoked to keep the potential constant. In "sealed-off" tubes the effect of the ions can be made entirely negligible. The first objective therefore was the investigation of secondary emission properties of certain phosphors. Since in most practical applications it is possible to make contact with the phosphor either by supporting it on conducting material or by making contact at the edge, the second objective was to determine the resistivity of phosphors under operating conditions.

With the potential of the luminescent material known, it is clear that the third and fourth objectives of this study would naturally be the determination of the light output as a function of the true bombarding potential of the phosphor relative to the cathode and as a function of the current density.

Tube and Circuit Design

The sketch shown in Fig. 1 shows the essential parts of the tube used. This drawing has been prepared to illustrate certain features of construction rather than attempt to draw an exact reproduction of the tube. Seven single lead tungsten-to-glass seals were arranged around the end of a large Pyrex "test-tube" with a bottom view lay-out as shown in Fig. 1b. A side tube with a short tungsten seal for mounting the "getter ring" was sealed as shown in Fig. 1a, and the blank thus prepared was connected to an exceptionally good vacuum system for the preliminary baking of three or four hours at 500°C. This served to anneal the glass partially and give the seals a rigorous test since the oven was allowed to cool very slowly after this bake. The blank was then cracked open by using a hot wire at the point marked "crack-off" and the metal parts which had all been vigorously heat treated in a separate blank were assembled as shown. The parts were carefully aligned so as to be concentric and the slits 1 and 2 properly located.

Two "fernico" wires 20 mils in diameter and 10 cm long were imbedded in small tubes of 705-AO glass. At one end, these were in turn melted into a small plate of this glass which was finally ground to form a flat rectangular plate 0.55 cm by 0.95 cm with short sections of the "fernico" exposed as shown in Fig. 1c. The phosphor was applied to this surface by one of the following three methods. (1) An air operated spray gun was used for the moderately fine grain phosphors which were suspended in acetone. The grains were sufficiently course so that constant agitation by air bubbling was needed to keep the phosphor in suspension. The spray was operated in this way until the coating was thick enough to hide completely the "fernico" wires lying in the surface of the test plate. (2) The *very fine* grain phosphors were furnished to me in the form of a "milk-like" suspension in acetone. In this case the grains were so fine that some hours were required for the phosphor to settle out after the suspension had been agitated. The grain size was estimated to average approximately 3×10^{-5} cm

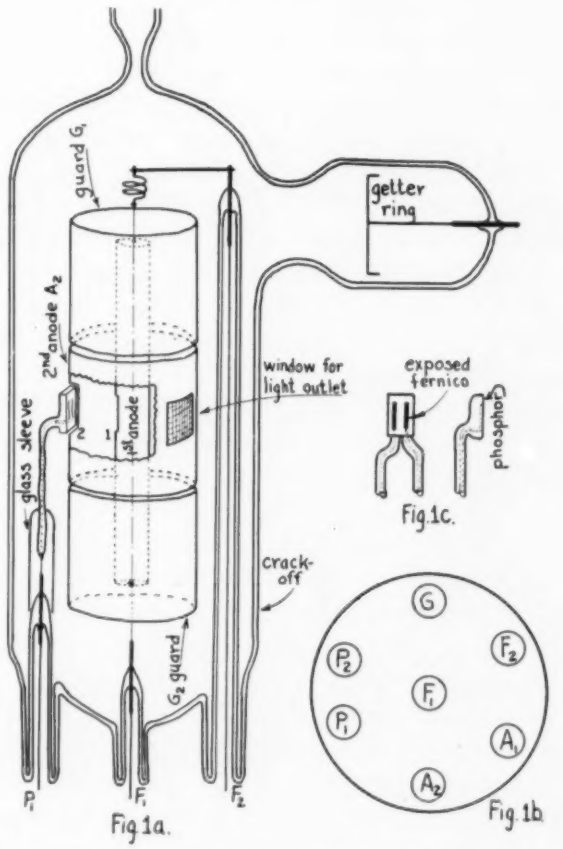

Fig. 1. (a) Sketch of tube. (b) Bottom layout of tube blank. (c) Test plate with "fernico" wires exposed in surface.

in diameter. It was found quite practical to place a single drop of this suspension on the test plate and allow the acetone to evaporate thus leaving a uniform and well adhering coating of the phosphor. (3) Still a third method used for very coarse grains utilized a water solution of potassium silicate for a binder.

After the test sample was prepared, movable glass sleeves were slid over the two glass-covered wires which formed the support of the test sample. These wires were welded to the tungsten leads marked P_1 and P_2 in Fig. 1 in such a manner that the test plate fitted into the 0.6 cm by 1.0 cm opening in the second anode shown as A_2. After the welding was completed the glass sleeves were adjusted to cover the welds completely. These sleeves were formed so as to fit very closely over the glass-covered "fernico" wires and also over the glass of the tungsten-to-glass seal. It was very important that no part of the test plate leads be exposed to the direct arrival of electrons since the method used to study the electrical properties of the phosphor depended on the assumption that no charges could flow into the test plate connections except those which flowed through the phosphor.

A thoriated tungsten filament which had been polished smooth by grinding was used as the source of electrons because experience has shown that this type of filament emits electrons very uniformly after prolonged activation at about 1960°K subsequent to giving the filament the usual high temperature flashing at 2850°K. It was also possible, with this type of cathode, to open the tube as many times as desired to change the phosphor sample and at the same time not impair in any way the emission properties of the filament. Of course the filament had to be reactivated but this could be done with the same degree of perfection as often as was needed.

The four cylinders used for the first anode A_1, the second anode A_2 and the guard rings G_1 and G_2 were made from annealed 3 mil sheet tantalum and supported on tantalum wires so that these parts could be heated nearly to a "white-heat" by electron bombardment and induction heating. Short pieces of outgassed nickel were used to assemble these metal parts to the tungsten lead-in wires. Eight to ten aluminum-barium getter pellets[2] were welded in the form of a ring and mounted in the side-tube shown in Fig. 1. This construction was used because of the ease with which this unit could be cracked off to be cleaned and replenished with getter each time a new phosphor sample was put in the tube.

After the tube was completely assembled and sealed back together at the "crack-off," the exhaust schedule lasting between ten and thirty hours was started. After a one-hour bake at 500°C and about three hours at 470°C, during which time the liquid-air trap and the connection between it and the tube were also baked at the same temperature, liquid air was put on the trap and following this the "tube oven" and the "connection oven" were removed. The filament was then flashed and activated and the bombardment of the anodes begun. This was continued until a vacuum of the order of 10^{-8} mm of mercury was obtained with the first anode nearly at a "white-heat" and the getter ring at as bright a red as was considered the maximum which would not explode the getter. During the early stages of heat treatment it was found that the gas given off, rapidly deactivated the filament as indicated by a considerable decrease in electron emission. The time required to bring about this deactivation served as a better indication as to the condition of the tube than any measurements which could have been made with an ionization gauge. The tube was operated at about ten times the normal maximum load during this heat treatment in that ten to fifteen milliamperes of electron current flowed from the filament to the anodes with a difference in potential between the filament and these collecters of 10,000 volts. Most of the heat thus developed was radiated by the first anode and therefore the outer electrodes A_2, G_1 and G_2 were heated red hot by high frequency induction currents. The heat treatment of these outer elements was limited because it was feared that the glass test plate might melt. When it was found that under these conditions the filament remained well activated for a period of an hour or so, the seal-off capillary was softened and the getter ring heated to explode the

[2] Type C-400 barium-aluminum getters very kindly furnished by King Laboratories, Syracuse, N. Y., were found to be particularly satisfactory since they will withstand baking at 500°C for long periods of time without appreciable evaporation before firing.

getter. The tube was finally sealed off after another hour or so of heat treatment and pumping. After this rather vigorous exhaust schedule, the tube could be operated indefinitely at 10,000 volts with as much as one milliampere of current to the anodes without appreciable loss of activity of the cathode surface.

The diagram of the electrical circuit used for this study is shown in Fig. 2. Three power-packs using full-wave rectifiers and adequate filtering were connected as shown. Pack (Pa_2) maintained the required voltage difference between the second anode and the filament while pack (Pa_1) was used to maintain the first anode at any potential, relative to the second anode, that was needed. These power-packs and also the filament batteries were well insulated from ground. A third pack (Pa_g) was used to establish the second anode at any desired potential relative to ground. The test wires connected to the phosphor were always at ground potential as can be seen from the circuit diagram.

Measurement of Potential and Resistance of Phosphor While Bombarded by Electrons

The potential difference between the second anode and the cathode will be designated as V_{ac} while that between the second anode and the first anode will be given by V_{a1}. The symbol V_{ag} will be used to indicate the potential of the second anode relative to ground. The current to the anodes was controlled by varying the temperature of the filament. Although in general the current to the first anode was set at arbitrary values between 10^{-8} amp. and 3×10^{-3} amp., the current measured at the second anode was *assumed* to be directly proportional to the primary beam current. That it was necessary to make this assumption, is obviously a serious criticism of this work. Many experimental results such as the accurate proportionality between light output and current for low intensities gave "internal" evidence that this assumption was justified but none of these gave incontrovertible information. If this problem is reattacked with the aim of making it more quantitative than the present study, the tube should be so constructed that the primary beam current can be measured directly. The fraction of the primary beam which struck the phosphor on the test plate depended to a certain extent on the ratio of the potentials V_{a1} to V_{ac} since the slit in the first anode distorted

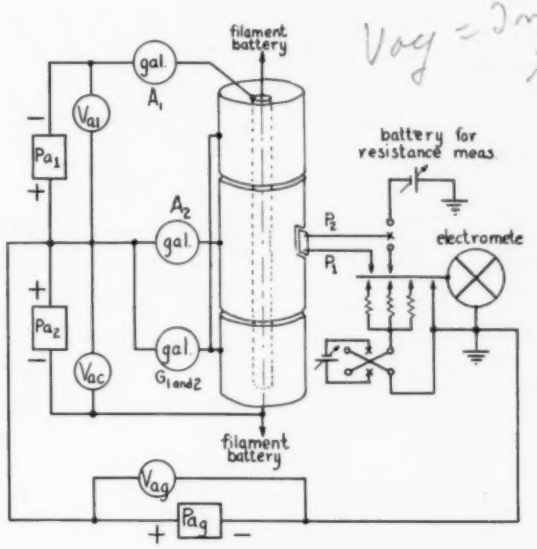

Fig. 2. Circuit diagram.

the equipotentials and thus created an electron lens which was converging or diverging depending upon the V_{a1} to V_{ac} ratio. Whenever measurements made at one value voltage V_{ac} were to be compared with those at another value of V_{ac}, the ratio V_{a1}/V_{ac} was maintained constant. With a filament diameter of 5.06×10^{-3} cm and first and second anode diameters of 1.0 and 3.81 cm, respectively, the ratio $(V_{a1}/V_{ac})=0.20$ gave the critical condition for an electron lens of infinite focal length at the slit in the first anode. The lens formula given by Calbick and Davisson[3] predicted correctly the potential ratio required to focus an electron image of the filament on the phosphor surface. This formula is $L=4(V_{ac}-V_{a1})/(G_2-G_1)$, where L is the focal length in cm and G_1 and G_2 are electric intensities in volts per cm on the inside and the outside of the first anode computed disregarding the slit.

Secondary electrons produced at the slit of the first anode or even inside this anode could strike the phosphor test surface in case it was positive with respect to this anode. If the phosphor was less than one or two hundred volts positive with

[3] C. J. Calbick and C. J. Davisson, Phys. Rev. **45**, 764 (1934).

respect to the first anode these secondaries tended to charge the surface to a more negative value relative to the second anode than it would have had in the absence of these low energy secondary electrons. On the other hand if the phosphor was between three hundred and a thousand volts positive with respect to the first anode then the secondary electrons arrived at the screen with enough energy to remove more than one electron for each of these electrons received at the screen. It will be shown below that as the energy of the primary electrons is increased a value is generally reached for which only one secondary electron is produced at the screen for each primary electron which strikes it. Unless some other agency is brought in, it is impossible to make the screen more positive with respect to the cathode than this limiting value. If only ten to twenty percent of the primary electron current is removed by conducting it away through the phosphor then a considerably higher cathode to screen voltage may be attained. Still another way of discharging the screen which might be worth consideration would be to bombard it with electrons from an electron "gun" entirely auxiliary to the principle electron gun of the tube. This auxiliary gun would spray the surface of the phosphor with a copious supply of three or four hundred volt electrons and since each one of these would produce more than one secondary electron at the screen, a considerably higher voltage difference could be maintained between the screen and the cathode of the principal gun of the tube.

With the circuit shown in Fig. 2, the potential of the insulated phosphor could always be determined with accuracy since this was obtained by adjusting the voltage of the power pack (Pa_g) to that particular voltage for which no current flowed in the electrometer circuit. Since this part of the circuit was so sensitive that a current less than 0.001 percent of the primary beam current could be measured easily, it was possible to determine V_{ag} with high precision. A necessary condition that such determinations were not faulty was that the voltage V_{ag} for zero current should be independent of the beam current and be the same for either probe wire P_1 or P_2 or for both of them together. In the rare cases where these tests were not satisfied, definite faults in the screen were discernible. Although the screen potential could be determined with accuracy under any particular set of conditions, the results were not always entirely free from ambiguity because of the effects of secondary emission from the first anode. A particularly striking example of the effect of secondary emission is illustrated by Fig. 3. Here the observed value of V_{ag} for zero current through the probe connections is plotted as the ordinate and the difference in potential between the first and second anodes is plotted as the abscissa. The potential of the second anode relative to the filament was constant at 2000 volts and the phosphor used for this was a zinc silicate (meta) supported by a potassium silicate binder. The resistance of this phosphor was the lowest of any measured.

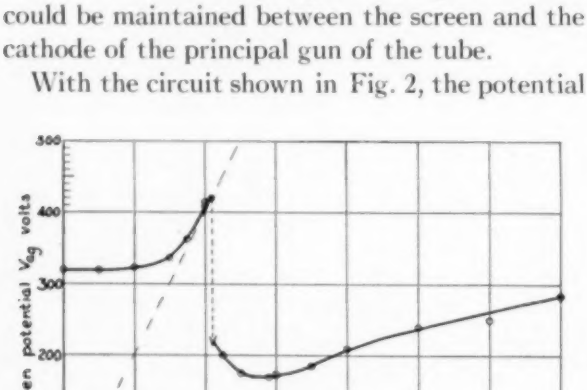

FIG. 3. Screen potential as a function of the first anode potential showing effect of secondary emission from first anode. $V_{ac}=2000$ volts.

The curve shown in Fig. 3 started with $V_{ag}=320$ volts when the first and second anodes had no difference in potential. It is certain that a negligible number of secondaries from the first anode reached the screen under this condition and therefore we can conclude that for this particular phosphor and binder, an insulated screen would charge up to a potential of about 300 volts negative with respect to the anode when the true energy of the bombarding electrons was 1700 volts. This is an abnormally large difference in potential for such low energy electrons but this curve was selected for discussion to illustrate as clearly as possible the effect of secondaries which took place as the first anode was made nearly as negative as the phosphor. At first the phosphor became still more negative with respect to the anode as it received the very low energy second-

aries which necessitated a drop in the primary beam energy from 1700 to 1600 volts in order to increase the normal secondary emission yield of the phosphor enough to make up for the arrival of the slow electrons. A discontinuity took place when V_{a1} was increased to 410 volts. The potential of the insulated screen changed suddenly over 200 volts and, with the first anode 570 volts negative to the second anode, the screen was only 170 volts negative as compared with 320 volts which was the true value for the primary electrons taken alone. Under these conditions, the difference in potential between the first anode and the screen was 400 volts which further study showed to be the electron energy value giving the maximum secondary emission yield for this particular phosphor. In all of the work described below care was exercised in order to interpret the results correctly and not allow the effects of secondary emission from the first anode to invalidate the final conclusions.

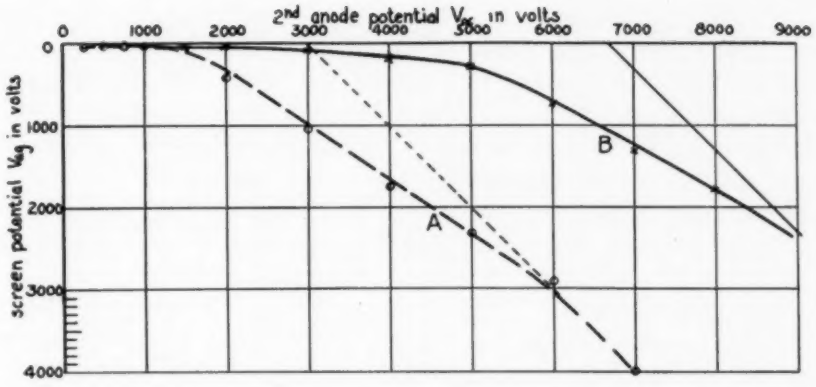

FIG. 4. Potential difference between screen and second anode as a function of second anode potential. *A*, coarse grain phosphor with potassium silicate binder. *B*, very fine grain phosphor with no binder.

The two curves shown in Fig. 4 illustrate the nature of the results obtained. These curves should be compared with that of Fig. 13 which was obtained with an experimental nine-inch cathode-ray tube with a very high current density (10^{-2} amp. per sq. cm) in the beam. The main points of interest in these curves are (1) at low voltages there is very little difference in potential between the screen and the second anode: (2) at higher voltages large differences come in and (3) a limit is reached as V_{ac} is increased such that the potential V_{ag} increases just as rapidly as V_{ac}. When this limit is reached it is impossible to obtain any increase in the bombarding electron energy by increasing the anode potential unless some other means of discharging the screen is used besides that of the simple production of secondary electrons by the primary beam. The two methods most commonly used are (1) screen conductivity and (2) the use of positive ions produced along the path of the primary beam. As was pointed out above, a third method perhaps worth trying would be to use an auxiliary electron gun.

It is obvious from the curves of Fig. 4 that zinc orthosilicate can have very different secondary emission properties depending on the method of handling it or on the type of binder used and the kind of impurities that may be present. Curve "A" was observed with a coarse grained phosphor held to the test plate by a potassium silicate binder and curve "B" was obtained with a very fine grained phosphor put on the test plate by the "drop" method described above. One phosphor studied which happened to have a maximum attainable potential of only 5600 volts in its normal state was found to change this maximum to about 8000 volts as a result of the evaporation of a small amount of thorium from the filament on to the surface of the phosphor. The thorium evaporated over probably formed on the average less than a monatomic layer. The increase in the voltage maximum thus obtained was not permanent and the experiment was useful only to indicate that very small amounts of impurity are needed to modify the secondary emission properties very considerably.

With the circuit arrangements as shown in Fig. 2, the resistance of the phosphor could be measured when it was not being electron bombarded by measuring the current flowing around the circuit as a function of the voltage difference applied between the probe wires. The current was found to be a linear function of the voltage up to

ten volts in either direction. Tests were not made with higher voltages. In order to measure the resistance of the phosphor while it was being bombarded, it was first necessary to set the voltage V_{ag} to that value for which no current flowed in the probe wire connected directly to the electrometer. This was done with the other probe connection open. After satisfying this condition an e.m.f. of about one volt was connected between the probe wires and the current flowing in the electrometer circuit due to this e.m.f. was measured. In all experiments of this kind which were tried there was no difference in the resistance due to the bombarding electrons except in cases where the heating effect was great. In most cases it was possible to reduce the resistance to one-half its original value by heating the phosphor with electron bombardment. The fact that this was a heating effect was shown by measuring the resistance as a function of the time after the bombarding current was turned off. The rate of increase of resistance seemed to be very reasonably accounted for by the time required for the tube parts to cool off. In one case the entire tube was heated using external heaters. A temperature rise from 25°C to about 50°C brought about a 50 percent decrease in phosphor resistance. Determinations of the resistance of four different

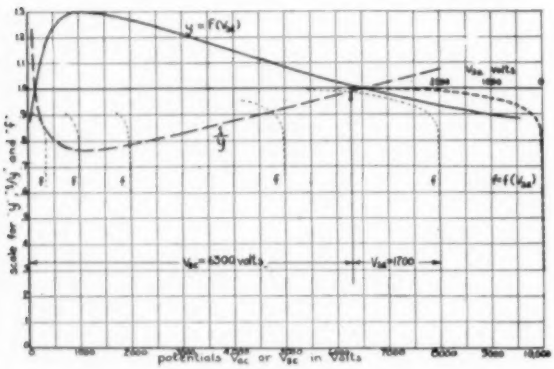

FIG. 5. Hypothetical curves to explain stabilization of screen potentials.

phosphors gave 72 megohms and 1400 megohms for two fine grain samples and 6.3 megohms and 250 megohms for two coarse grain samples which were held to the glass plate by a potassium silicate binder. The wide range of variation in the resistance of these phosphors indicates that further study of the conduction properties of phosphors is really much needed because of the important part conductivity may play in the functioning of cathode-ray tubes operated at high voltages.

EXPLANATION OF POTENTIAL MEASUREMENTS WITH HYPOTHETICAL CURVES

With the help of the hypothetical curves of Fig. 5, it is easy to understand the main features of the curves of Fig. 4. Let the primary beam current reaching the phosphor be i_p and the "saturation" secondary emission current be i_s. This means that the idealized secondary emission yield should be a function of the screen to cathode potential (V_{sc}) and given by

$$(i_s/i_p)=y=F(V_{sc}). \tag{1}$$

A likely form of this function is shown by the solid line of Fig. 5. The idealized saturation emission is to be distinguished from the *actual* secondary emission current (i_a) collected by the anode since the latter depends on geometrical factors and also on the potentials applied to the elements within the measuring tube. Of these potentials, the voltage difference between the screen and the anode (V_{sa}), will be the most important. The function $f(V_{sa})$ shown by the dotted line at the extreme right of Fig. 5 is defined by the following relation

$$(i_a/i_s)=f=f(V_{sa}). \tag{2}$$

This function $f=f(V_{sa})$ may be described as the fraction of the ideal secondary emission current which actually arrives at the anode. The condition which must be satisfied for a perfectly insulated screen to have a stable screen potential while being bombarded by a homogeneous beam of primary electrons is given in the following equation which is expressed in its three forms,

$$i_p=i_a, \tag{3a}$$

$$(i_s/y)=i_sf, \tag{3b}$$

$$(1/y)=f. \tag{3c}$$

Eq. (3c) shows that a simple graphical method of

visualizing the process by which the screen potential is established, will be obtained if the function $(1/y)$ is plotted and intersections between it and a "movable" f curve are determined. The examples shown in Fig. 5 are for V_{ac} values of 350; 1000; 2000; 5000; 8000 and 10,000 volts. For these cases the intersections are seen to come at values of screen to cathode potential (V_{sc}) of 300; 990; 1980; 4750; 6300 and 6500 volts. The differences between the corresponding values given, indicate the expected potential differences between the screen and the anode.

It is easy to see by this example why one must expect that the potential of an insulated phosphor will differ very little from that of the anode for potentials above four or five hundred volts and also why large differences in potential will develop when the anode potential exceeds that at which the secondary emission yield is unity. In the case shown this occurs at 6500 volts. After passing this point of unit yield, it is quite likely that y does not fall by more than fifteen or twenty percent as the screen to cathode potential is increased by three or four thousand volts. If conductivity or secondary emission from an auxiliary electron source which is bombarding the screen with five- or six-hundred-volt electrons, is introduced to take care of the excess electrons, then a worthwhile increase in the effective screen potential will result. It would also be of value to investigate means of increasing the normal secondary emission by the deposition of very thin surface layers.

In order to understand the performance of a given phosphor more quantitatively, it might be of value to determine by direct measurement the form of the curve $F(V_{sc})$. It could be done by bombarding the surface with two independent electron guns so well designed that a reasonably uniform beam of accurately measurable intensity could be focused on to a small circular glass target with probe wires so as to use the electrometer method of measuring the screen potential. By finding combinations of beam intensity and beam energy which keep the phosphor test plate at definite potentials relative to the cathode or the anode, it should be possible to obtain quite an accurate determination of the true secondary emission yield $F(V_{sc})$.

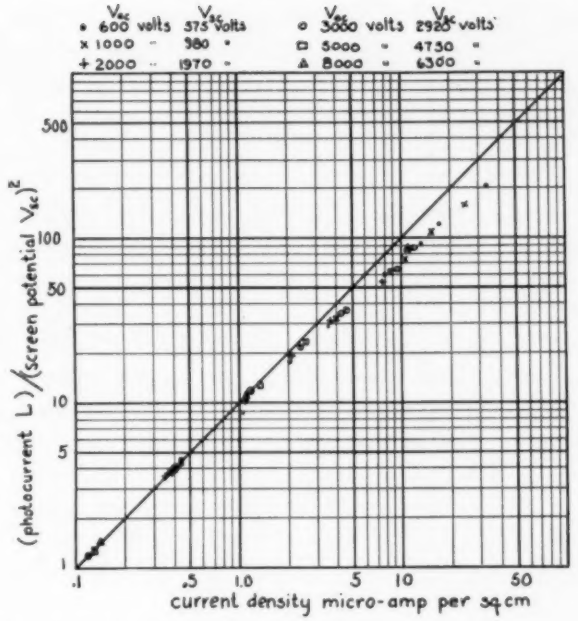

FIG. 6. Log of light output as a function of log of current density.

PHOTOTUBE CONSTRUCTION FOR LUMINOSITY MEASUREMENTS

A commercial photoelectric cell was set up to measure the light output from the phosphor but this attempt failed for two reasons. The light output from the filament produced a photocurrent many times larger than that due to the luminosity of the phosphor when an intense electron beam was used. The difficulty could have been eliminated by using a filter to cut off all of the infrared sensitivity. This was not done because experiment showed that the "dark current" was so great that the cell could not be used for the weaker intensities of light and it was clearly necessary to measure these weak intensities if the work was to be of value. The second trial was made with a potassium photoelectric cell made by condensing the metal on the inside of a small spherical glass bulb.[4] The anode was supported on a well insulated side tube. From the standpoint of sensitivity and freedom from "dark current" this tube was perfectly satisfactory. A new difficulty developed which is mentioned here in order to put other experimenters on their guard when using similar tubes for measuring very weak light intensities.

[4] W. B. Nottingham, J. Frank. Inst. **205**, 637 (1928).

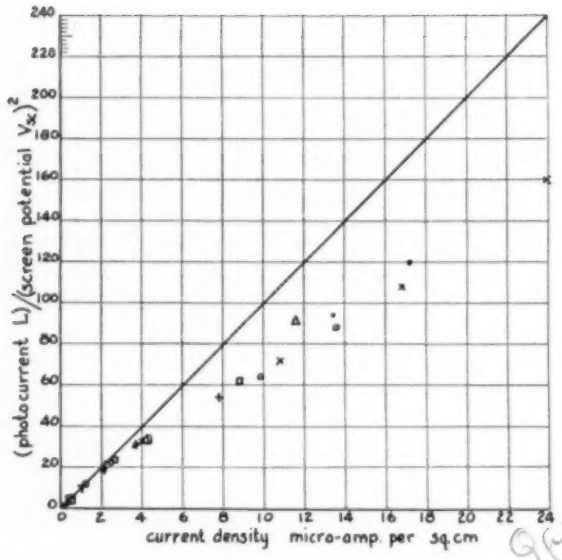

FIG. 7. Light output as a function of current density. See Fig. 6 for symbols.

In making one of these tubes it is inevitable that a few droplets of potassium will become detached from the main body of potassium forming the photoelectric cathode on the inside wall of the tube. These droplets, generally at the boundary line of the window or at the beginning of the insulated support of the anode, charged up positively and reached anode potential after which they became inactive as photoelectric emitters. If the current measured was large, then these islands of emission surface were quickly charged and the cell operated quite normally with no apparent trouble. If the current was small an apparent "fatigue" was observed since the islands at first contributed to the photoelectric current for a time depending on the intensity of the light. Some time was required for the islands to return to cathode potential after the light was cut off. This restored the cell to full sensitivity and the process could be repeated. These changes in photoelectric current were observed and at first attributed to a "fatigue" effect in the phosphor. The true explanation of the effect was discovered and a new phototube constructed which was entirely free from any such difficulty.

The new photoelectric cell was made by mounting a tantalum "pill box" 3.8 cm in diameter and 4.0 cm high on a single lead tungsten-to-glass seal. The box had two openings of which one was in one end and the other in the middle of the side of the cylinder. The latter served as the window to admit the light and since the opening was one centimeter square it was covered by a "grid" of fine tantalum wires spaced about 0.1 cm apart. The anode was made from a tantalum strip 0.5 cm wide and 4 cm long and was bent in the form of a springy hoop and welded to a second single lead seal. The opening in the end plate of the "pill box" was made in the center and was just large enough to permit the anode to slide in when squeezed. A rather open seal-off constriction was attached to the glass envelope so as to point directly through this hole in the end plate. The axis of the constriction made an angle of about forty degrees with the axis of the tube. The anode seal was reentrant and about ten centimeters long so as to allow plenty of room for a long external leakage path and a guard ring which also furnished the means of supporting the tube. After the tube was thoroughly baked and the tantalum box outgassed, potassium which had been carefully distilled was shot through the constriction to give a good coating of clean potassium inside the "pill box."

The phototube was carefully shielded so that no induced charges would affect the measuring system when large changes in potential were made at the main tube. The entire system was also shielded to reduce the effect of outside disturbances and to eliminate all stray light. The photoelectric currents were measured by determining the drop produced by the current over a high resistance. A series of these were used varying from 10^8 ohms to 1.5×10^{10} ohms. An FP-54 tube used with a DuBridge-Brown[5] circuit served as the indicator to show when the "IR" drop was exactly balanced out by a measured e.m.f. With the amplifier sensitivity used of 5 mm per millivolt, a photoelectric current of 10^{-13} amp. could be measured with the required accuracy.

LIGHT OUTPUT AS A FUNCTION OF CURRENT DENSITY

Although it is often assumed that the light output from a phosphor is directly proportional to the current density when the area covered and the bombarding electron energy are constant, the

[5] L. A. DuBridge and H. Brown, R. S. I. **4**, 532 (1933).

work of Levy and West[6] as well as the present study shows that there is a definite saturation effect as the current density is increased. The published data of Levy and West cover a wide variety of phosphors but show results for only one voltage and also there is some question as to the accuracy of their results at low intensities since the curves, which are plotted on a linear scale, do not pass through the origin of the graph.

The data here presented suffer from the fact that they apply to only one type of phosphor, namely willemite, but on the other hand they cover a very wide range of intensity and a wide range in voltage. The results shown in Fig. 6 are typical of many curves taken on a number of different samples of willemite obtained from different sources. In order to explain the method used in plotting Figs. 6 and 7, it will be necessary to anticipate a result which will be discussed in considerable detail in the next section of this paper. Over the low voltage range for all phosphors and over the entire *observable* range for some phosphors, the following empirical equation has been found[7] to represent the observed data with accuracy.

$$L = Q(i) \cdot (V_{sc} - V_0)^2. \qquad (4)$$

Here L is the light intensity, V_{sc} is the *screen* to cathode potential, V_0 is a constant which might very well be called the "dead voltage," and $Q(i)$ is a function of the *current density* which, according to these experiments, is the same for all samples of willemite tested. For the particular sample from which the data shown in Figs. 6 and 7 were obtained, the "dead voltage" V_0 was found to be zero and therefore a plot of (L/V_{sc}^2) as a function of the current density (i) gives a graphical representation of the function $Q(i)$ as shown in Fig. 7. The method of plotting used in Fig. 6 is in many ways more instructive since the use of "log" scales for both the abscissa and the ordinate brings out the true nature of the function in a striking manner. Over a very wide range of current density below 2.5 microamperes per sq. cm the light output was accurately directly proportional to the current density as shown by Fig. 6, since the experimental points fall along the straight line of unit slope which may be extrapolated as far into the high current region as needed. If the observed points fall below this line a saturation effect is indicated. We may define the expression relative "efficiency" as the ratio of the observed light output at any specified current density to that read on the straight line at this same current density. With this definition we see that at 20 microamperes per sq. cm the "efficiency" has dropped to 65 percent. Another way of stating it is that 35 percent of the light which one might expect to obtain is lost due to some saturation effect. As will be shown later in this paper the "efficiency" drops to about two percent when the current density is increased as high as *ten milliamperes* per sq. cm (see Fig. 14).

If Eq. (4) is written in the logarithmic form as follows,

$$\log_{10} L = \log_{10} Q(i) + \log_{10} V(V_{sc}), \qquad (5)$$

it is clear that when the voltage is held constant, plots of $\log_{10} L$ against $\log_{10} i$ will superpose on each other if the saturation for a given phosphor is independent of the bombarding voltage. Nearly one hundred sets of measurements have been made on nine different samples of willemite at screen voltages from 500 to 6500 volts, and in all cases the function $Q(i)$ was the same within the experimental error. The difficulty of determining the "absolute" current density was the largest source of error and this is thought not to exceed ten or fifteen percent. Relative measurements were all accurate to within about two percent.

It is very surprising indeed that the function $Q(i)$ should be the same for all of the samples of willemite because there certainly must have been considerable difference in the concentration of "activator" present and also a difference in the state of strain in the various cases because of differences in heat treatment used in preparation. It is hoped that a systematic study can be made of this saturation effect since it is quite likely to be of importance from the standpoint of a more complete understanding of the atomic processes involved and also from the practical point of view since an increase in luminous output of ten or twenty to one at the very high current densities is not too much to hope for if this saturation loss can be greatly reduced.

Although there are important advantages in

[6] L. Levy and D. W. West, J. I. E. E. **79**, 11 (1936).
[7] W. B. Nottingham, Phys. Rev. **51**, 591 (1937) and Phys. Rev. **51**, 1008 (1937).

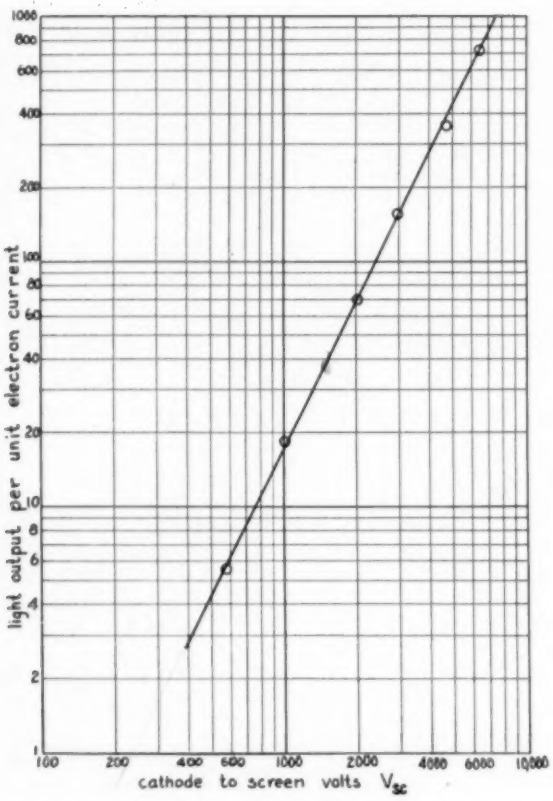

FIG. 8. Light output as a function of the bombarding energy in volts. Moderately fine grain zinc orthosilicate.

the use of the photoelectric cell for accurate measurements of light intensity, there are also certain limitations in its use. In the first place it is generally necessary to use one of the standard visual methods of measurement in order to convert the photoelectric current values into luminosity units. This can be done under conditions most favorable for accurate measurements with the illuminometer which one chooses to use and then the photoelectric cell can be utilized to make rapid and accurate relative measurements over a very wide range in intensity. In general it is very necessary that there be no change in the spectral quality of the light. This is especially important when the range of wavelengths used falls in a part of the spectrum over which the sensitivity of the cell changes very rapidly with wave-length as is the case when a potassium photoelectric cell is used to measure the green light emitted by willemite under electron bombardment. It is generally assumed that the true spectral distribution found in the light emitted is independent of the electron energy and current density and no evidence was found in these studies to indicate the contrary. In case this work is extended an attempt will be made to test this point since the results depend very definitely on the truth of this assumption.

Light Output as a Function of Electron Energy

The Lenard[8] law for the variation of luminosity with electron energy is

$$L=(1/C)\cdot Q\cdot(v-v_0), \tag{6}$$

where C is a constant, Q the "beam" intensity, v the electron energy and v_0 the "dead" voltage. This law has been used extensively as a practical empirical equation as for example by Leverenz[9] and does serve to represent a limited range of some observed data especially when the anode potential is used as a measure of the electron energy instead of the true screen potential. The work of Levy and West[6] shows that the candlepower increases more rapidly than the first power of the voltage although they do not make a detailed analysis of their data. An investigation by Brown[10] led him to conclude that for the electron energy range up to about 800 volts, the brightness B is given by the formula $B=KJV^2$ where K is a constant. J the current density, and V the anode potential. This formula is a special case of that given in Eq. (4) which was arrived at quite independently.

The procedure found most convenient in these studies involved the observation of the luminosity as a function of the current while the potentials of all electrodes were maintained constant. For a given sample this was done at quite a number of voltages on the second anode generally between 500 volts and 8000 volts. The voltage on the first anode relative to the second was adjusted so as to bear a constant ratio to the voltage V_{ac} of either 0.2 or 0.02. This was necessary in order to keep the electron trajectories the same at all voltages. An individual set of points shown in Fig. 6, will serve to illustrate the kind of experimental data obtained although the photoelectric current was plotted as a function of the current to the second anode instead

[8] P. Lenard, Ann. d. Physik, **12**, 449 (1903).
[9] H. W. Leverenz, J. O. S. A. **27**, 25 (1937).
[10] T. B. Brown, J. O. S. A. **27**, 186 (1937).

of using the photocurrent divided by the square of the screen potential as in Fig. 6. For each voltage studied, the light intensity per unit anode current was obtained by reading off the value of photoelectric current found on the straight line of unit slope on each plot at a specified value of anode current such as one microampere. The table of values thus prepared served as the basis of plots similar to those of Figs. 8 and 9. The results presented in Fig. 8 are for an RCA zinc orthosilicate with an average grain size thought to be about 2×10^{-4} cm in diameter supported on glass without binder. The range in voltage used on the second anode for this set of data was from 600 volts to 8000 volts. With an anode voltage of 8000 volts the screen potential was observed to be 1550 volts negative with respect to the second anode. This large difference in potential between the screen and the anode caused a reduction in the proportion of the primary beam which arrived at the test surface. Early in this investigation, it was recognized that a correction of this kind would have to be made whenever large differences in potential developed between the screen and the anode and for this reason a tube was constructed with a carefully built Faraday cage located in the aperture usually occupied by the phosphor test plate. In spite of the care used in the design of the cage secondary emission from the cage made it impossible to measure the

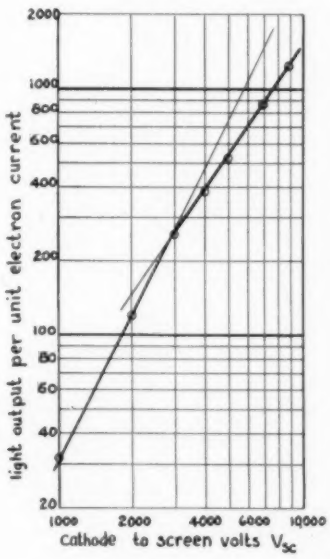

FIG. 9. Light output as a function of bombarding energy in volts. Very fine grain zinc orthosilicate.

spreading effect on the primary beam brought about by the difference in potential between the cage and the second anode when high voltages were used. As the second anode voltage was reduced to less than fifty volts curves taken were found to approach a limiting curve which was independent of the actual voltage but depended only on the voltage ratios used. Two curves taken at twenty and thirty volts were identical. Corrections thus arrived at and used in connection with the data in Figs. 8 and 9 are tabulated in Table I.

TABLE I.

FRACTION OF PRIMARY BEAM STRIKING SCREEN	V_{sa}/V_{ac}
1.0	0
0.9	0.1
0.83	0.2
0.77	0.3
0.71	0.4
0.65	0.5

Later an attempt was made to test this correction curve by depositing a very thin layer of phosphor on a conducting plate and using the variation of the light emitted as a measure of the spreading of the electron beam when the screen to cathode voltage was constant and the second anode voltage varied. The test was not satisfactory because of the poor alignment of the filament. Unfortunately it was not possible to repeat this experiment although it would no doubt give more reliable results than the Faraday cage method used.

The straight line through the points of Fig. 8 is drawn with a slope of *two* with no correction for "dead" voltage. The fact that such a correction is logical and is related to the average surface condition of the grains of the phosphor was illustrated by experiments with a coarse grain phosphor which was held to the test plate by a considerable amount of potassium silicate put on to find out what effect it might have. In this case the "dead" voltage turned out to be 450 volts. This was found in two ways. First the light intensity per unit beam current was plotted as the ordinate on log-log paper and the screen potential was plotted along the abscissa. The curve thus produced had a slope of the order of

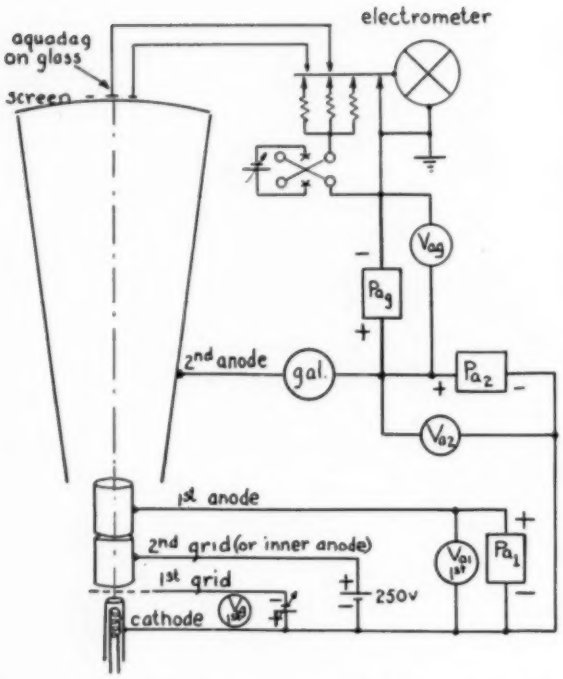

FIG. 10. Diagram of circuit used with RCA C-730 tube investigation.

three or four at the lower end and approached a slope of two at the upper end. "Dead" voltage corrections of 400, 450, and 500 volts were tried and it was found that the 450 volt correction gave the best straight line and at the same time the slope of the line was very nearly two. If one had a good reason to believe that Eq. (4) had the correct form theoretically, then the best way of finding a good value of the constant V_0 would be to plot the square root of the light per unit beam current as a function of the screen potential and determine the intercept on the voltage axis. This method was also used in this case and V_0 was found to be 450 volts as expected. The fact that the constant V_0 respresents an *average* property of the phosphor was brought out by studies of this surface which had such a high "dead" voltage. Although the light output for voltages below 450 volts was so weak that it could not be measured with the photoelectric system used, it was observable by eye down to about 300 volts.

The results shown in Fig. 9 are for a very fine grain phosphor. The average grain size was thought to be about 3×10^{-5} cm in diameter. Such small particles are difficult to measure and it is possible that some of the grains were four or five times smaller than this and some were certainly three times larger. This phosphor was deposited by the "drop" method from a milk-like suspension of the material. The analysis again showed that the light intensity increased with the square of the screen potential for voltages below 3000 volts but for voltages above this the light output increased as the 1.41 power of the electron energy expressed in volts. It is interesting to note that the penetrating power of three-thousand-volt electrons is 2.25×10^{-5} cm for Zn_2SiO_4 according to the calculations of Leverenz.[9] On the basis of the small evidence so far obtained it is not possible to draw conclusions with certainty but one can see that the indications are that the light output from a phosphor increases as the square of the bombarding voltage unless the surface layer of the phosphor grains is disturbed in the grinding process or is covered with some impurity such as a silicate binder. This rule seems to hold for all phosphors studied up to the highest voltages obtainable depending on the secondary emission properties of the grain, if the bombarding energy is not sufficient to penetrate completely the individual grains of the phosphor.

Screen Potentials and Luminosity Measurements as Found by Using an Experimental Nine-Inch Cathode-Ray Tube[11]

The C-730 tube has an electron gun with an indirectly heated cathode, a control grid, an inner anode maintained at a constant potential, and an outer anode known as the "first anode" of the tube. A conducting coating on the inside of the tube is known as the "second anode." The focusing of the electron beam depends almost

[11] The results discussed in this section were obtained by using an experimental model of a nine-inch cathode-ray tube with the numerical designation C-730 which the Research and Engineering Department of the Radiotron Division of RCA Manufacturing Company very kindly loaned me for the time required for these tests. The results should not be taken as in any way representative of expected performance of this type of tube but must be understood to apply to this particular tube. The reason for publishing this information as it stands is that it brings out the relationship existing between many of the fundamental properties of phosphors disclosed by the investigations reported above and the performance of a phosphor in a tube of a practical design.

entirely on the ratio of the first and second anode potentials, and the intensity of the beam is governed by the potential of the control grid. Preliminary experiments using magnetic deflections and also tests of the current characteristics as observed at each collector in the tube, seemed to indicate that its performance was remarkably free from any disturbing influence of either unwanted secondary emission or gas effects. Dr. Herbert Nelson[12] of the Radiotron Division of the RCA Manufacturing Company, has experimented with the problem of determining the screen potential in a tube of this kind by painting a disk of "aquadag" on the outside surface of the glass and then while the glass was heated to a temperature of two or three hundred degrees centigrade by means of a hot air blast he found the potential relative to the second anode at which the disk had to be maintained so that no current flowed through the glass from the phosphor to the disk.

A diagram of the circuit used for the study of the screen potential as a function of current density and second anode voltage is shown in Fig. 10. A Compton electrometer was used to measure the currents received by the "aquadag" contact on the outside of the tube. Three contacts were made near the center of the screen area of the tube. The innermost one was a circle 0.6 cm in diameter filled in solid with "aquadag" and around this were alternate rings of non-painted and painted surface each one of which was 0.5 cm wide. This system of two conducting rings and a center formed a target like arrangement of contacts and by means of a weak bar magnet the electron beam was deflected so as to strike near the center of the "bullseye" when the beam was focused.

With a constant bombarding voltage of 2000 volts and a beam current of 120×10^{-6} amp the electrometer current was measured as a function of the voltage and the slope of the curve showed the effective resistance of the Nelson "heat-contact" to be 7500 megohms when a moderate blast of hot air was used. This could be reduced to 1000 megohms by increasing the temperature of the blast. Since the electrometer was sufficiently sensitive so that the lower temperature blast was perfectly satisfactory, this was used for all of the measurements to be described below.

The measurements made with the second anode voltage at 8000 volts were in some ways the most striking and are therefore shown in Fig. 11. With 1000 volts on the first anode the diameter of the beam at the screen was about 1.7 cm and the difference in potential between the "aquadag" and the second anode was only 55 volts with 270×10^{-6} amp. beam current. (See curve *A*.) With a beam current of 160×10^{-6} amp. the difference in potential was 44 volts. The current densities for these two cases compute out to be 120×10^{-6} and 70×10^{-6} amp. per sq. cm. As the potential on the first anode was increased, the electron beam came to a focus and then diverged again. At the focal point, the current densities for curves *A* and *B* of Fig. 11 were about 5×10^{-3} and 3×10^{-3} amp. per sq. cm, respectively and the potential differences were 1350 and 690 volts. Measurements with still higher current densities gave a limiting difference in potential of 1650 volts. It seems certain from these results as well as from observations taken with a wide range of lower second anode potentials that not all of the beam current is taken away from the screen by *simple secondary emission*. An obvious means at hand is that of conductivity through the screen to the second anode which is in contact with the phosphor.

The resistance *R* of a thin sheet of conducting

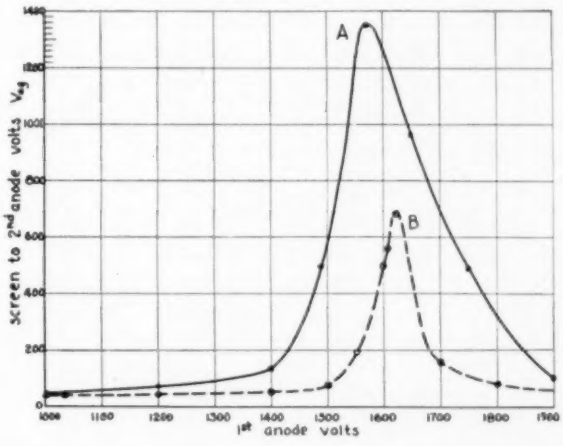

FIG. 11. Variation of "screen" potential with first anode or focusing voltage. Second anode voltage constant at 8000 volts. Curve *A*, grid −10 volts, beam current from 270×10^{-6} to 375×10^{-6}. Curve *B*, grid −15 volts, beam current from 160×10^{-6} to 225×10^{-6}.

[12] The results of Dr. Nelson's extensive investigations with the "heat contact" which he devised are to be published in the near future.

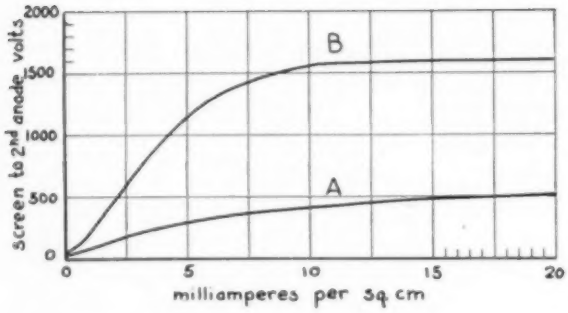

FIG. 12. Anode to screen potential as a function of current density. Curve A, 7000 volts on second anode. Curve B, 8000 volts on second anode.

material of uniform resistivity ρ which is in the form of a ring of inside radius r_1 and outside radius r_2 is given by the formula

$$R=(\rho/2\pi)\cdot\ln(r_2/r_1). \tag{7}$$

The resistivity ρ is expressed in ohms and is the resistance across a square of any size since the resistance of such a surface is assumed to be proportional to the distance between the contacts along two sides of the square and inversely proportional to the length of the sides along which contact is made. If the resistivity of the screen were assumed to be 25 megohms, then for the case described above for which the beam diameter was 1.7 cm the resistance of the screen from the periphery of the beam to the second anode would be 10 megohms. With 55 volts as the difference in potential, 5.5×10^{-6} amp. would flow through the screen to the anode. This would be only two percent of the beam current. If the focused beam had a radius of only 0.02 cm the resistance of the screen would rise to only 25 megohms and yet the screen potential increased to 690 volts for curve B and 1350 volts for curve A. The assumption of a resistivity as low as 25 megohms was made in order to make the calculations as favorable as possible in support of the conductivity hypothesis. These calculations seem to show that direct conductivity to the second anode cannot be responsible for the great change in screen potential with increasing current density.

Two other possibilities seem to be worth further consideration which are first an assumed nonuniformity in the secondary emission properties of the surface. In this case the "active" secondary emission areas would receive electrons from the less active regions by conductivity which would give rise to a considerable difference in potential from one small region to another over the surface. The experiments so far performed give no corroborating evidence in support of this hypothesis. A second possibility is that there is a space charge effect at the surface of the phosphor since the secondary electrons have relatively small initial velocities and might require a large difference in potential between the focal point and the second anode in order to accelerate these electrons away. Again this hypothesis does not quite fit the facts as illustrated in Figs. 12 and 13.

Figure 12 shows curves A and B which represent, for 7000 and for 8000 volts on the second anode, the difference in potential between the screen and the second anode as a function of the current density. Because of the difficulty of measuring the area of the spot on the screen in the very short time during which the beam was permitted to bombard the surface and also because of the nonuniformity in the distribution of current over the beam, the points serving as the basis for the curves of Fig. 12 were rather scattered and yet it is thought that these curves are nevertheless worth reporting. The curve given in Fig. 13 bears such a complete resemblance to those of Fig. 4 that one is tempted to conclude that this represents the true behavior of the phosphor when not complicated by the complex phenomena which are responsible for the great change in screen potential as the current density in the beam is decreased. This conclusion cannot be made with reasonable certainty without further investigation.

The potassium-on-tantalum photoelectric cell, described above was used to measure the light output from the C-730 tube. A region not far from the center of the screen was selected which was free from imperfections in light distribution over the area of the beam. Here a circular opening one square centimeter in area was defined by painting "aquadag" on the end of the tube. A short focal lens was used to receive the light and focus it on the window of the photoelectric cell. Between the lens and the screen a mirror was mounted on a support so that it could be swung into place directly in front of the circular opening

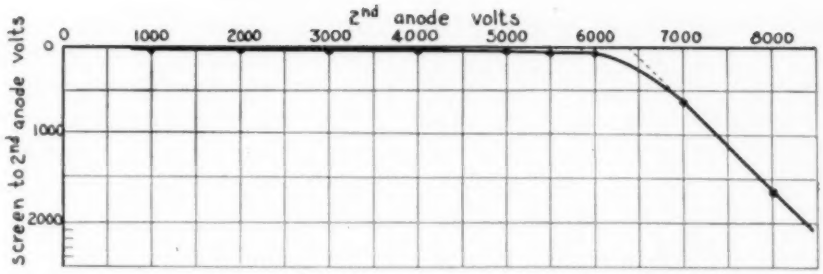

FIG. 13. Screen to anode potential as a function of the second anode potential for very high current densities.

painted on the glass and in this way it was possible to adjust the size of the beam to fill the opening exactly and also properly center it. The thickness of the glass was so great that it was impossible to locate the beam properly without the use of the mirror. With the voltage on the second anode constant, the light output was measured as a function of the current in the beam. The current to the second anode thus indicated the current density directly since the cross-section area was maintained constant at one sq. cm. For each different voltage the light output was plotted as a function of the current density on log-log paper. These curves were found to superpose on each other to within the accuracy of the experiments again indicating that the saturation effect found in the previous studies depended only on the current density and was independent of the bombarding electron energy. Measurements made using higher electron densities and a smaller beam diameter fit in also with the data using the standard one sq. cm spot size. All of the results are therefore combined together in Fig. 14. The solid line was drawn through the points which numbered about a hundred in all and the two dash lines were drawn so as to include all of the observations between them. Most of the points taken were for current densities less than 5×10^{-4} amp. and therefore the lower part of the curve can be said to be more certain than the part above 5×10^{-4} amp. which was determined by only six points. The data shown in Fig. 6 agree within the experimental error with the curve of Fig. 14. There is little doubt but that current densities of the order of 10^{-2} amp. per sq. cm will be used in practical tubes and if this experience is at all universal then such tubes will be operating at an efficiency far below what one might reasonably hope for. Fig. 14 shows that 98 percent of the light is lost due to the saturation effect for this particular phosphor at a current density of 10^{-2} amp. per sq. cm.

Figure 15 illustrates the results obtained for the variation of light output with second anode voltage. These data were taken by observing the light output as a function of the current density at different voltages and then after plotting these data as described above, the light output per unit current density was determined by selecting a point on the straight line portion of the log-log plot. It was noticed that after the screen was severely bombarded at high voltage and high current density, the light output with a standard low voltage and low current condition was observed to decrease. For this reason a systematic study of the light output as a function of the voltage was not undertaken using the region of the screen originally selected but another was found which had not been bombarded so strongly. The current densities used on this second one square centimeter circular opening were not allowed to exceed 10^{-5} amp. per sq. cm. The first run was made at 3000 volts on the second anode and after this ten more runs were made at lower

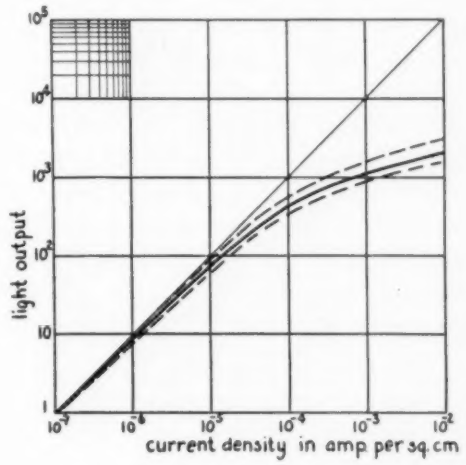

FIG. 14. Light output as a function of current density. Individual curves for all voltages from 500 to 9600 volts superimposed by vertical shift only.

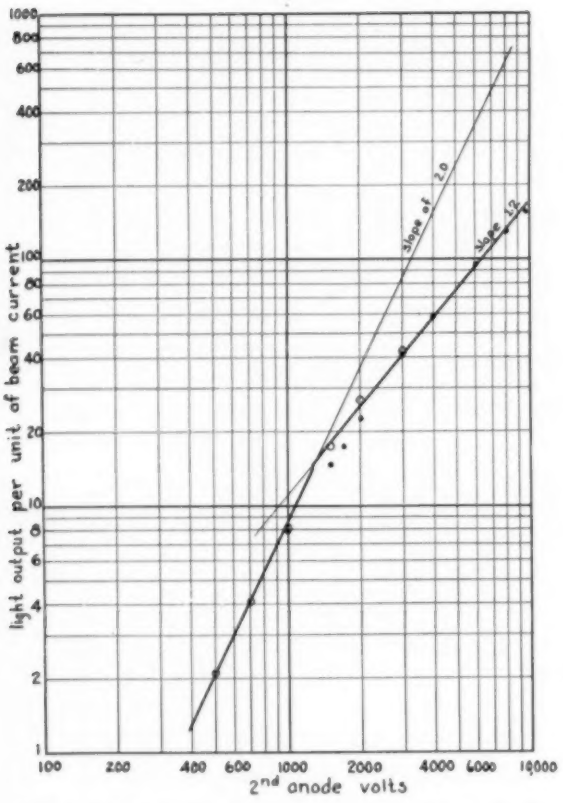

FIG. 15. Light output per unit current density as a function of the bombarding electron energy. Circles for initial operation at voltages below 3000 volts, dots show change in light output after high voltage bombardment.

voltages down to 500 volts. These results were accurately reproducible and are represented by the circles of Fig. 15. Following this runs were made at higher voltages and then a run was made at 1700 volts. This point shown by a dot is obviously below the value expected by interpolation by about 25 percent. More low voltage data were taken and although these were again reproducible, the results obtained in the transition region between 1000 and 2000 volts showed that a permanent change had been undergone by the phosphor. The two straight lines drawn through the points of Fig. 15 have 2.0 and 1.2 for their slopes and thus confirm the previous results illustrated by Figs. 8 and 9 that for low electron energies the light output increases with the square of the bombarding voltage. The reason for the failure of this rule above about 1500 volts should be investigated further since an increase of some five- to tenfold in the light intensity could be obtained if by using a larger grain size for example the range of application of the "square law" could be extended.

A possible explanation for the change in the rate of increase of light output with voltage is that a voltage difference between the screen and the anode was developing at the higher anode voltages in spite of the fact that the measurements using the Nelson "heat contact" showed that very little difference in potential should exist for these low current densities even up to the highest voltages used. Since the screen potential measurements were made with the glass and the screen hot, it was considered worth while to observe the effect of the application of the hot air blast on the light output. With 9600 volts on the anode, an increase in temperature first caused a 25 percent *increase* in the light while a further increase in temperature reduced the light output to 10 percent below that observed at room temperature. The same effect was observed to a less marked degree at 8000 volts. These experiments thus turned out to be inconclusive because of the complex nature of the phenomena involved and again indicate the importance of pursuing the investigation further.

The author's most sincere thanks are hereby extended to the members of the staffs at both the Harrison and the Camden laboratories of the RCA Manufacturing Company who have assisted so extensively with these studies and especially to Dr. V. K. Zworykin, Dr. G. R. Shaw, and Dr. L. B. Headrick. I am also indebted to Dr. A. W. Hull and Dr. G. R. Fonda for the opportunity of discussing the results with them. For the faithful technical service and assistance rendered, I owe much to Messrs. J. Ryan, L. W. Ryan and A. B. White.

The Cathode Region in the Glow Discharge

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(Received July 24, 1937)

The present study of the cathode region in the glow discharge is divided into three sections: I. The range of the electrons in the negative glow. II. Positive ion formation in the Crookes dark space. III. Energy of the electron entering the negative glow. I. The length of the negative glow and the drop in potential across the Crookes dark space have been measured simultaneously for various gases over a wide current and pressure range. The observed lengths correspond exactly to the range of electrons as determined by Lehmann for voltages equivalent to the cathode potential drop. From this it is concluded that the energy of the electrons entering the negative glow must correspond to the entire difference in potential across the dark space. II. The length of the Crookes dark space has been measured under various conditions and the values obtained compared with the mean free path between ionizing collisions as given by Tate and Smith. The number of positive ions found in the dark space per electron of current has been computed by making use of Aston's equation for the potential distribution and Tate's values for the efficiency of ionization as a function of voltage. The number of positive ions so computed is, in general, materially less than one per electron; this contrasts sharply with from 50 to 100 estimated by some investigators. III. The energy distribution of the electron entering the negative glow has been measured by the deflection method, a nonhomogeneity of velocity in the electron beam being discernible by an elongation of the fluorescent spot on a Willemite screw. No change in the shape of the spot was detected for the electrons leaving the dark space although an elongation of it was observed for electrons in the negative glow. The experimental arrangement was such that fluctuations in voltage of more than 10 percent could have been observed. The general conclusion to be drawn from these studies is that the energy of the electrons entering the negative glow corresponds closely to the entire cathode potential drop, and that only a small fraction of the energy of the electrons leaving the cathode is expended in the Crookes dark space. A possible mechanism for the cathode region is briefly outlined.

THE most widely accepted theory for the cathode region in the glow discharge is that developed by H. A. Wilson.[1] The theory assumes that electrons are liberated from the cathode by positive ion bombardment and that ionization occurs by collision with electrons and positive ions in the fall space, increasing exponentially according to the Townsend equation.

Using this theory as a basis for their calculations Compton and Morse,[2] and Linder and Davis[3] have computed the ratio of positive to negative carriers at the cathode to be between 50 and 100 to 1, while at the edge of the negative glow they compute the current to be carried almost entirely by electrons. Linder[4] and more recently Emeleus and Kennedy,[5] by further extending the theory, have concluded that as much as 85 percent of the energy is dissipated in the dark space, while the remainder is expended in the negative glow.

Since the basic concepts underlying the mechanism of the discharge employed by the above investigators were developed before quantitative information was available regarding the behavior of electrons under conditions simulated in the discharge, it seems possible that several of its postulates can now be subjected to experimental verification. In consequence it is proposed in the present paper (1) to contrast the length of the negative glow with the range of electrons of known energy, (2) to compare the length of the Crookes dark space with the mean free path between ionizing collisions as given by Tate and Smith, and (3) to test the distribution of velocity of the electrons entering the negative glow.

I. Length of the Negative Glow

The discharge tube used in these tests was 40 cm long and 4.5 cm in diameter. The electrodes were of aluminum backed with iron so that their position could be changed with an external magnet. A liquid-air trap was sealed directly to the side of the tube to facilitate the removal of mercury vapor and to enable all chemically reactive gases to be removed by passing a discharge from an electrode in the tube

* Now at the U. S. Patent Office.
[1] H. A. Wilson, Phys. Rev. **8**, 227 (1916).
[2] K. T. Compton and P. M. Morse, Phys. Rev. **30**, 305 (1928).
[3] E. G. Linder and A. P. Davis, J. Phys. Chem. **35**, 3649 (1931).
[4] E. G. Linder, Phys. Rev. **38**, 679 (1931).
[5] Emeleus and Kennedy, Phil. Mag. **18**, 874 (1934).

to an auxiliary electrode beyond the trap.[6] In addition, the usual precautions were taken in purifying the gases. With the exception of argon which contained about 0.4 percent nitrogen the final gases were estimated to contain less than 0.01 percent impurity. The electrodes were well worked in with the gas in question before readings were made; the spectrum of mercury was absent from the discharge.

The boundaries of the negative glow were measured by means of two sets of movable vanes and also by a movable direct reading spectroscope, the points where the characteristic line spectrum becomes invisible being taken as the limits. The two methods checked to within the limits of experimental error.

The cathode fall of potential was measured with a Weston voltmeter; the minimum value observed when the anode was moved through the negative glow was taken as the potential fall. The potential drop in the negative glow was negligible, being of the order of a few volts.

[6] Note: See "Chemical Action in the Glow Discharge," I to XIV, A. Keith Brewer *et al.*, J. Phys. Chem. (1929–1934).

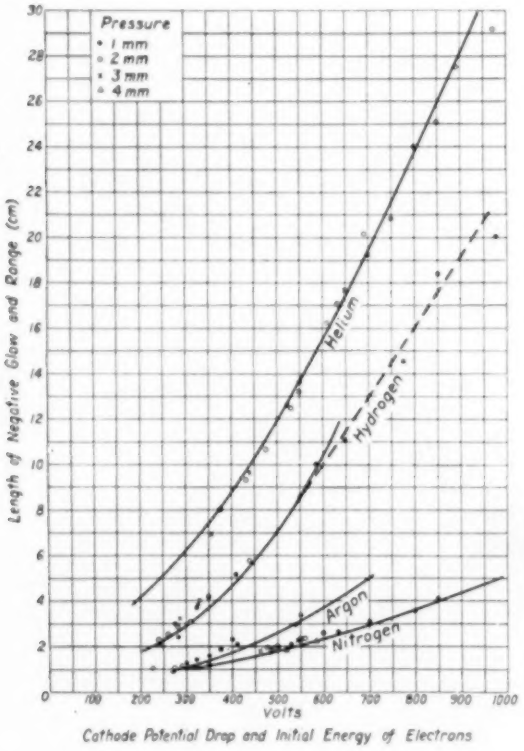

FIG. 1.

In Fig. 1 are plotted the lengths of the negative glow as a function of the cathode potential drop. The points were taken at the pressures given and were corrected to 1 mm pressure. The various points given for each pressure were obtained by varying the discharge current.

The lines in Fig. 1 are not drawn to the observed points but are those given by Lehmann[7] for the range of electrons as a function of voltage. The broken line for hydrogen is an extension of Lehmann's line as indicated by the present data. It will be noted that the observed points for the length of the negative glow as a function of the full cathode potential fall fit the curves of Lehmann for corresponding voltages to within the limits of experimental error. The conclusion follows, therefore, that an appreciable fraction if not most of the electrons entering the negative glow from the Crookes dark space must have a range corresponding to the entire cathode potential drop.

II. Ionization in the Crookes Dark Space

The length of the Crookes dark space as a function of pressure and voltage was measured in the discharge tube described in the previous section. The observed lengths are plotted as broken lines in Fig. 2.

The points marked with (o) are computed from Aston's equation;[8] the computed and observed values agree perfectly for nitrogen and hydrogen although the present values for helium are appreciably longer than those computed from Aston's constants. Aston, however, claims no accuracy for his helium values; the helium in the present case appeared spectroscopically pure. In fitting Aston's equation to the present data it is necessary to apply a correction below 0.2 mm to account for the shrinkage of the discharge away from the edge of the cathode.

The solid lines in Fig. 2 are the values for the mean free path between ionizing collisions computed from the data for ϵ; ϵ is the number of positive ions formed per cm of path, obtained from the data of Smith[9] for helium, and from Tate and Smith[10] for hydrogen and nitrogen.

[7] J. F. Lehmann, Proc. Roy. Soc. **115**, 624 (1927).
[8] F. W. Aston and H. E. Watson, Proc. Roy. Soc. **86**, 168 (1912).
[9] P. T. Smith, Phys. Rev. **36**, 1293 (1930).
[10] J. T. Tate and P. T. Smith, Phys. Rev. **39**, 270 (1932).

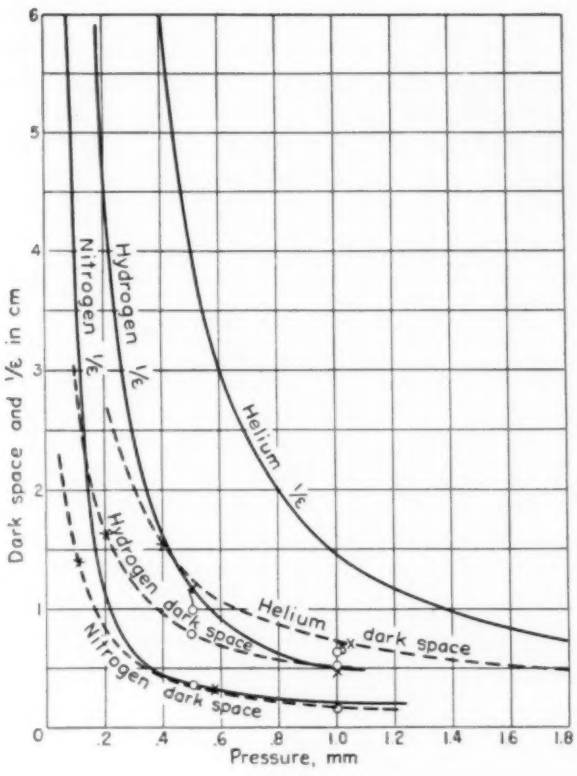

FIG. 2.

The values given are for voltages corresponding to the entire cathode potential drop.

The number of positive ions formed per electron in traveling through one mean free path between ionizing collisions can be obtained from the following considerations. Out of N_0 electrons starting from the cathode $N=N_0e^{-x\epsilon}$ will have a path exceeding x cm in length. Thus $N_0 \cdot 1/e$ is the fractional number which have not produced ions in going a distance $1/\epsilon$, while $(1-1/e)N_0$ is the number of ions formed by N_0 electrons in going this distance. $(1-1/e)N_0/N_0=0.63$ is therefore the number of positive ions formed per electron in traveling $1/\epsilon$ cm.

Since the cathode fall is several hundred volts and since the ionization efficiency[10] starts from zero at the ionization potential, and passes through a maximum in the neighborhood of 100 volts, a comparison of the length of the dark space with $1/\epsilon$, as illustrated in Fig. 2, serves only to show that the number of positive ions formed in the dark space is of the order of 0.5 to 1.0 per electron.

A reasonably accurate estimation of the number of positive ions formed per electron in the Crookes dark space can be made by a graphical method of calculation. A volt *v.s.* distance from the cathode curve for the potential distribution in the dark space was divided into small segments in which the ionization efficiency did not change materially. Aston's equation $V/V_0=d^2-(d-x)^2/d^2$ was used in computing the form of the curve. The number of positive ions formed by each primary electron leaving the cathode (I_p^+) and by each secondary electron liberated in the fall space (I_s^+) was then calculated for each segment. Probe measurements indicate that the effect of the positive space charge may be more pronounced than that given by Aston's equation. This will tend to lower the number of ions formed in the dark space; the form of the potential curve, however, cannot change the results by any significant amount.

In Table I are given the number of ionizing collisions made in the dark space by primary electrons (I_p^+), and by secondary electron (I_s^+), as well as the total number of positive ions formed (I_T^+). These calculations are made for the points marked with an X in Fig. 2.

The data show clearly that the number of positive ions formed in the dark space is less than 1 per electron leaving the cathode. This is in distinct contrast to the 100 computed by Linder and Davis, and by Emeleus and Kennedy.

The energy expended in the dark space (E_{ds}) is given in the last column. These values were computed from the energy required to form an ion pair as given by Lehmann ($H_e^+=31$ volts, $H_2^+=37$ volts, $N_2^+=45$ volts). These results are again in contrast to those of Emeleus and Kennedy who compute about 85 percent of the energy is expended in the dark space.

TABLE I.

Gas	P	I_p^+	I_s^+	I_T^+	E_{ds}
H_2	1.02 mm	0.84	0.31	1.15	15.5%
H_2	0.203	0.21	0.11	0.32	6.2
H_e	1.03	0.39	0.09	0.48	7.5
H_e	0.40	0.21	0.06	0.27	3.7
N_2	0.58	0.84	0.36	1.20	29.4
N_2	0.108	0.45	0.14	0.59	5.1

P—pressure in mm Hg.
I_p^+—positive ions formed by primary electrons.
I_s^+—positive ions formed in dark space for each electron leaving the cathode.
E_{ds}—percent energy of electrons expended in the dark space.

III. Energy of the Electrons Entering the Negative Glow

Sir J. J. Thomson[11] has measured the distribution of energy among the electrons entering the negative glow by deflection methods. The electrons leaving the dark space were allowed to pass through a capillary and were then deflected in electric and magnetic fields. The results showed that all the electrons were of uniform velocity and possessed an energy corresponding to the entire cathode potential drop. A criticism of these results may be raised in that it is possible that the passage through the long capillary removed all the electrons except those which had not suffered collision while passing through the dark space.

In order to test for the possible presence of a low energy component among the electrons passing through the dark space the experiment of Thomson was repeated, using a knife edge perforation in the anode in place of the long capillary. The distance between the willemite screen and the perforation was 9 cm. The cathode rays were deflected with a magnetic field. The results confirmed those of Thomson in that no enlargement of the spot or tendency to tail was observed upon deflection for electrons entering the negative glow. As the cathode was moved back to introduce negative glow, a small lengthening of the spot was observed suggesting some inhomogeneity at the end of the glow.

The cathode potential was varied from 400 to 30,000 volts in these experiments. The relation between energy and radius of curvature of the deflected eletrons is given by $r=k\sqrt{V}$. For a 1000 volt electron a change of 100 volts is readily detectable. Thus, since 45 volts are required to produce a positive ion, not more than two ions can be formed per electron in the dark space without materially changing the shape of the spot. This does not represent an expenditure of more than 10 percent of the total energy of the electron. The presence of any appreciable accumulative ionization in the dark space can easily be detected by this method.

The above results are consistent with those presented in sections I and II in that they again indicate that the dissipation of energy in the Crookes dark space is small.

While it is not the purpose of this paper to present a mechanism for the entire cathode region, it is evident that a theory which depends on accumulative ionization and high dissipation of energy in the dark space is inconsistent with the facts presented above. It may be mentioned, however, that the pictures of the cathode region presented by Sir J. J. Thomson[11] and by J. W. Ryde[12] satisfy the demands of these experiments.

A possible explanation of the relatively large number of electrons liberated for each positive ion reaching the cathode[13] may be found in the adion theory of lowered work function for electron emission. It can be shown by the method of Becker[14] that if the ions upon reaching the cathode have an adsorbed life sufficient to maintain the surface in a state one-sixth covered with positive ions, the work function will be lowered to a point where the liberation of the necessary electrons by the existing fields will be possible.

The authors wish to thank Dr. L. R. Maxwell for his suggestions and for confirming the results on the uniformity of the velocity of the electrons passing through the dark space with his electron diffraction apparatus.

[11] Sir J. J. Thomson, Phil. Mag. **48**, 4 (1924).

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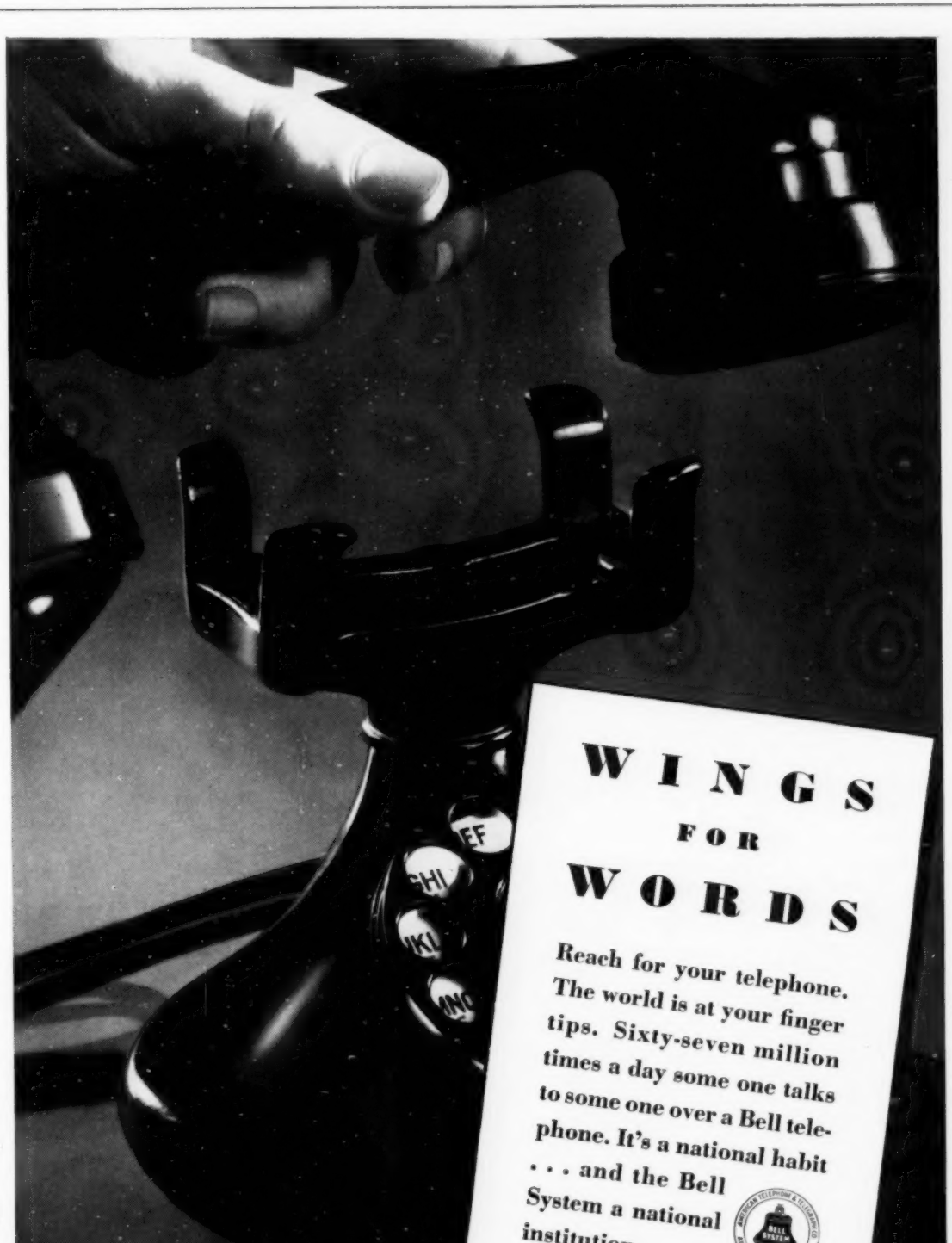
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American Physics Teacher

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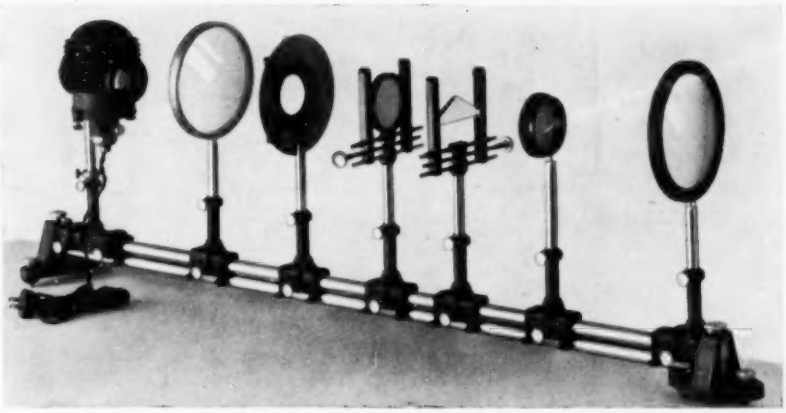

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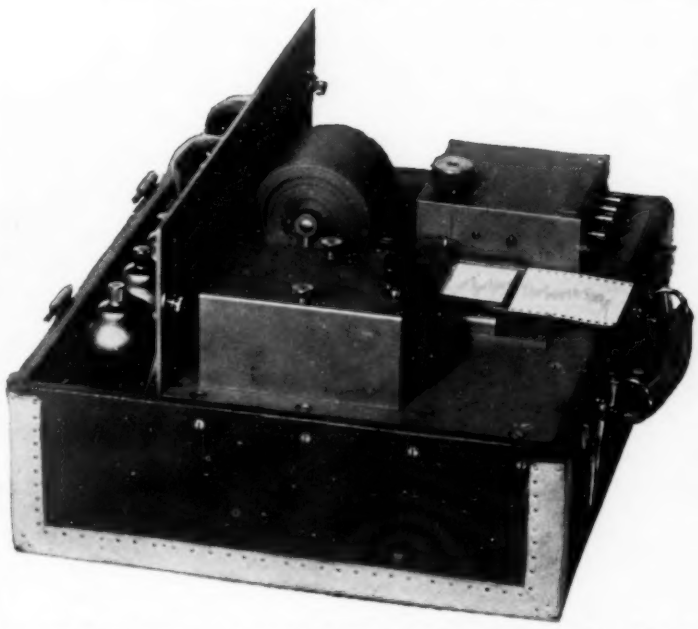

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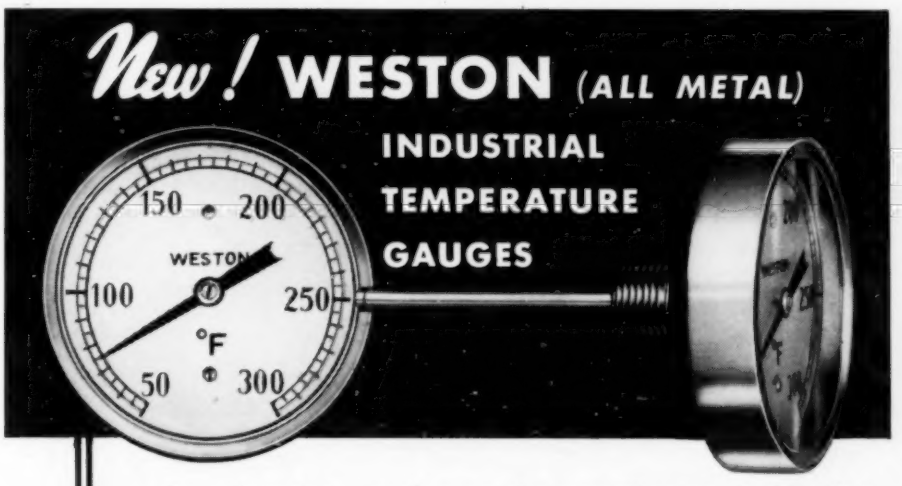

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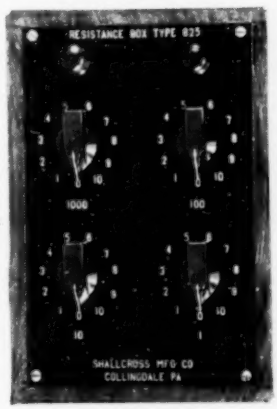

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